Monte Carlo calculations of correction factors for plane-parallel ionization chambers in clinical electron dosimetry

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Recent standard dosimetry protocols recommend that plane-parallel ionization chambers be used in the measurements of depth-dose distributions or the calibration of low-energy electron beams with beam quality \( R_{50} < 4 \) g/cm\(^2\). In electron dosimetry protocols with the plane-parallel chambers, the wall correction factor, \( P_{\text{wall}} \), in water is assumed to be unity and the replacement correction factor, \( P_{\text{repl}} \), is taken to be unity for well-guarded plane-parallel chambers, at all measurement depths. This study calculated \( P_{\text{wall}} \) and \( P_{\text{repl}} \) for NACP-02, Markus, and Roos plane-parallel chambers in clinical electron dosimetry using the EGSnrc Monte Carlo code system. The \( P_{\text{wall}} \) values for the plane-parallel chambers increased rapidly as a function of depth in water, especially at lower energy. The value around \( R_{50} \) for NACP-02 was about 10% greater than unity at 4 MeV. The effect was smaller for higher electron energies. Similarly, \( P_{\text{repl}} \) values with depth increased drastically in the region with the steep dose gradient for lower energy. For Markus \( P_{\text{repl}} \) departed more than 10% from unity close to \( R_{50} \) due to the narrow guard ring width. \( P_{\text{repl}} \) for NACP-02 and Roos was close to unity in the plateau region of depth-dose curves that includes a reference depth, \( d_{\text{ref}} \). It was also found that the ratio of the dose to water and the dose to the sensitive volume in the air cavity for the plane-parallel chambers, \( D_{\text{w}}/[D_{\text{air}}]_{\text{pp}} \), at \( d_{\text{ref}} \) differed significantly from that assumed by electron dosimetry protocols. © 2008 American Association of Physicists in Medicine. [DOI: 10.1118/1.2968102]

Key words: wall correction factor, replacement correction factor, plane-parallel ionization chamber, electron dosimetry, Monte Carlo calculations

I. INTRODUCTION

Recent standard dosimetry protocols\(^1-4\) recommend that plane-parallel ionization chambers be used in depth-dose measurements for high-energy electron beams. This is because the replacement correction factor \( P_{\text{repl}} \) for cylindrical ionization chambers is not known well as a function of a depth in water. In electron dosimetry protocols with the plane-parallel chambers, the wall correction factor \( P_{\text{wall}} \) in water is assumed to be unity and \( P_{\text{repl}} \) is taken to be unity for well-guarded plane-parallel chambers, at all measurement depths. Plane-parallel chambers are also recommended for the calibration of low-energy electron beams with beam qualities \( R_{50} < 4 \) g/cm\(^2\) or less than \( \bar{E}_{0} = 10 \) MeV, because the depth of measurement is more unambiguously defined. \( R_{50} \) is defined as the half-value depth of a dose in water.

Monte Carlo calculations are a good method of investigating \( P_{\text{wall}} \) and \( P_{\text{repl}} \) factors. Sempau et al.\(^5\) evaluated beam quality factors for plane-parallel chambers using the PENELOPE system. Their results show that the overall perturbation factor (the product of \( P_{\text{wall}} \) and \( P_{\text{repl}} \)) at the reference depth \( d_{\text{ref}} \) for the NACP-02 and PPC-40 chambers is different by approximately 0.5% at low electron energy (\( R_{50} = 1.4 \) cm) compared to that of the TRS-398 protocol when the factor is assumed to be unity at \( R_{50} = 8.75 \) cm. Recently, Buckley and Rogers\(^6\) calculated the \( P_{\text{wall}} \) correction for the combination of a water phantom and wall materials of plane-parallel chambers (NACP-02, Markus and Roos, etc.), using the EGSnrc Monte Carlo user-code CSnrc. When compared to the assumptions of standard dosimetry protocols, which use \( P_{\text{wall}} \) values of unity in electron beams, the calculated \( P_{\text{wall}} \) values show corrections of 1.7%–0.8% at \( d_{\text{ref}} \) for an NACP-02 chamber, over a range of nominal energies from 5 MeV (\( R_{50} = 2.08 \) cm) to 21 MeV (\( R_{50} = 8.3 \) cm). Similarly, the \( P_{\text{wall}} \) values are 1.25%–0.4% and 1.2%–0.5% for Roos and Markus chambers, respectively. The \( P_{\text{wall}} \) values are also more than 6% greater than unity with increasing depth of measurement at 6 MeV. Verhaegen et al.\(^7\) also reported \( P_{\text{wall}} \) values as a function of depth of measurement for the NACP-02 chamber in a water phantom. More recently, Zink and Wulff\(^8\) calculated \( P_{\text{wall}} \) values at \( d_{\text{ref}} \) in water for the Roos chamber. The investigations of Verhaegen et al.\(^7\) and Zink and Wulff\(^8\) are calculated using the same EGSnrc Monte Carlo system with different user-codes and show similar results to those of Buckley and Rogers.\(^6\) McEwen et al.\(^9\) used an empirical method for the determination of \( P_{\text{wall}} \) for the NACP-02 chamber. The effect is up to 1.4% at \( R_{50} = 1.2 \) cm and shows a slightly smaller perturbation than Monte Carlo calculations. The results mentioned above indicate that the size of the \( P_{\text{wall}} \) correction for plane-parallel chambers should be estimated adequately in the electron dosimetry protocol.

In contrast, work on the \( P_{\text{repl}} \) correction\(^6,8,10\) for plane-parallel chambers using Monte Carlo calculations is limited...
to the values for the NACP-02 and Roos chambers at \( d_{\text{ref}} \) in water, and only for an NACP-02 chamber as a function of depth of measurement in water; recent work by Buckley and Rogers\(^6\) and Verhaegen et al.\(^3\) indicated the need for a replacement correction at depths greater than \( d_{\text{ref}} \). More recently, Wang and Rogers\(^10\) investigated the \( P_{\text{repl}} \) correction for the NACP-02 chamber as a function of depth of measurement in water in more detail. The correction depends on depth of measurement and varies from 0.992 to 1.035 at a depth between 0.5 cm and \( R_{50} \) for a 6 MeV (\( R_{50}=2.63 \) cm) beam. \( P_{\text{repl}} \) for NACP-02 is 0.9964 even at \( d_{\text{ref}} \) and the value is different from unity assumed in the electron dosimetry protocol.

The purpose of this study was to investigate the \( P_{\text{wall}} \) and \( P_{\text{repl}} \) correction factors for NACP-02, Markus and Roos chambers at a depth between near-surface and \( R_{50} \). The Markus chamber with a very small guard ring is a classic design and thus not recommended in recent codes of practice. However, the bench marking of the perturbation effects for the Markus chamber is a valuable contribution for previous experimental data. Both correction factors were calculated by the EGSnrc Monte Carlo code system in a range of 4 MeV (\( R_{50}=1.31 \) cm) to 18 MeV (\( R_{50}=7.6 \) cm) electron beams. Also, the ratio of the dose to water and the dose to the sensitive volume in the air cavity for the plane-parallel chambers was compared with the water-to-air stopping-power ratio to evaluate the overall correction factor. Furthermore, the dose ratio at \( d_{\text{ref}} \) was compared with that assumed by the TG-51 and TRS-398 protocols.

II. THEORY

The relationship of the dose to water, \( D_w \), and the dose to air in water, \( D_{\text{air}} \), is presented according to the Spencer–Attix cavity theory

\[
D_w = D_{\text{air}} \left( \frac{L}{\rho} \right)_w \tag{1}
\]

\( (L/\rho)_w \) is the average restricted mass collision stopping-power ratio of water to air. This formulation is based on an idealized case in which the wall and the air cavity of the ionization chamber do not perturb the electron spectrum.

In actual measurement, the presence of the chamber wall and the cavity will affect the electron fluence spectrum and therefore corrections are required to the Spencer–Attix cavity theory. The absorbed dose to water for a plane-parallel chamber can be expressed using two corrections as follows:

\[
D_w = [D_{\text{air}}]_{pp} \left( \frac{L}{\rho} \right)_w P_{\text{wall}} P_{\text{repl}} \tag{2}
\]

\([D_{\text{air}}]_{pp}\) is the dose to the sensitive volume in the air cavity for the chamber. \( P_{\text{wall}} \) accounts for the nonphantom equivalence of the chamber wall material. \( P_{\text{repl}} \) is the product of two components, \( P_{\text{fl}} \) and \( P_{\text{gr}} \). \( P_{\text{fl}} \) is the fluence correction factor that corrects for changes in the electron fluence spectrum due to the presence of the air cavity, predominantly the in-scattering of electrons that makes the electron fluence inside the cavity different from that in the medium in the absence of the cavity. For many plane-parallel chambers, \( P_{\text{fl}} \) is assumed to be unity, but is taken to be nonunity for chambers which are not well guarded. \( P_{\text{gr}} \) is the gradient correction factor that accounts for the shift upstream of the effective point of measurement of the chamber due to the cavity. For plane-parallel chambers, \( P_{\text{gr}} \) is taken as unity when the point of measurement is at the front of the air cavity.

III. METHODS AND MATERIALS

III.A. Monte Carlo simulations

The EGSnrc (Ref. 11)/BEAMnrc code (Refs. 12 and 13) was used to simulate electron beams emerging from a Varian Clinac linear accelerator (Varian Oncology Systems, Palo Alto, CA). The modeling of Monte Carlo simulations for an electron beam is described in previous papers.\(^14,15\) Phase space data were taken below the applicator with a 15 cm \(^2\) field size for all electron energies. The dose distributions for electron beams in water were calculated with the EGSnrc/DOSXYZnrc code\(^16\) using the phase space data as input. The SSD was 100 cm. The parameters used for simulation were: \( AE=0.521 \) MeV, \( ECUT=0.700 \) MeV, and \( AP =PCUT=0.01 \) MeV. The CPU used was a Pentium IV with a 3.2 GHz processor. The incident electron energy was adjusted to agree within 2\% between Monte Carlo calculated and measured dose distributions (central axis depth-dose curve and off-axis dose profile at a depth of dose maximum) in a water phantom. Table I presents the characteristics of clinical electron beams from the Varian Clinac linear accelerators. The reference depth \( d_{\text{ref}} \) is obtained from 0.6\( R_{50} \)–0.1 \( cm \).

<table>
<thead>
<tr>
<th>Machine</th>
<th>( E_{\text{nominal}} ) (MeV)</th>
<th>( R_{50} ) (cm)</th>
<th>( d_{\text{ref}} ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100C</td>
<td>4</td>
<td>1.31</td>
<td>0.69</td>
</tr>
<tr>
<td>21EX</td>
<td>6</td>
<td>2.37</td>
<td>1.32</td>
</tr>
<tr>
<td>9</td>
<td>5.59</td>
<td>2.05</td>
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</tr>
<tr>
<td>12</td>
<td>5.06</td>
<td>2.94</td>
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</tr>
<tr>
<td>15</td>
<td>6.27</td>
<td>3.66</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>7.60</td>
<td>4.46</td>
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</tbody>
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FIG. 1. Simplified schematic diagram of the two geometries used to compute \( P_{\text{wall}} \). \( P_{\text{wall}} \) is computed as the ratio of doses \([D_{\text{air}}]_{w}\)/\([D_{\text{air}}]_{pp}\) using the CAWRZnrc code. \([D_{\text{air}}]_{w}\) is the dose to the sensitive volume in the air cavity for a chamber wall composed entirely of water, and \([D_{\text{air}}]_{pp}\) is the dose to a chamber with a detailed model of the realistic chamber wall.
clinical electron beams from the Varian Clinac linear accelerators used in this study.

Phase space data scored were also used to calculate wall correction factors and replacement correction factors for plane-parallel chambers, and Spencer–Attix water-to-air stopping-power ratios. Both correction factors and stopping-power ratios were calculated using EGSnrc user-codes CA VRZnrc, DOSRZnrc, and SPRRZnrc codes. The doses calculated in the cavity and the phantom affect energy thresholds for photon and electron transport, AE and ECUT. Wang calculated in the cavity and the phantom equal for the chamber. The ratio of doses water-to-air stopping-power ratio shown in Eq. (a) is computed from the relationship of the ratio of doses $D_{w}/[D_{air}]_{pp}$, and the ratio of doses and the stopping-power ratio are calculated using the DOSRZnrc, CA VRZnrc, and SPRRZnrc codes.

III.B. Calculation of wall correction factor $P_{wall}$ and replacement correction factor $P_{repl}$

The values of $P_{wall}$ and $P_{repl}$ for plane-parallel chambers were calculated at a depth between near-surface and $R_{50}$ using Monte Carlo methods. Figure 1 shows a schematic representation of how the calculation geometries are arranged to compute the $P_{wall}$ correction factor. $P_{wall}$ was computed as the ratio of doses $[D_{air}]_{w}/[D_{air}]_{pp}$ using the CA VRZnrc code. $[D_{air}]_{w}$ is the dose to the sensitive volume in the air cavity for a chamber wall composed entirely of water. The volume is defined by the electrode diameter and the separation. $[D_{air}]_{pp}$ is the dose to a real chamber geometry shown in Eq. (2). Figure 1 demonstrates simple chamber geometries, but in CAVRZnrc calculations, detailed chamber geometries were used according to the manufacturers’ specifications.

The $P_{repl}$ correction factor was computed from the relationship of the ratio of doses $D_{w}/[D_{air}]_{w}$ in the calculation geometries shown in Fig. 2 and the water-to-air stopping-power ratios. $D_{w}$ is the dose to water and calculated for a 0.1 mm thick slab with a front face at a depth in water equal to the point of measurement for the chamber, using the DOS-

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Schematic diagram of the two geometries used to compute $P_{repl}$. $P_{repl}$ is computed from the relationship of the ratio of doses $D_{w}/[D_{air}]_{w}$ and the ratio of doses and the stopping-power ratio shown in Eq. (a).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{Calculated dosimetric quantities for an NACP-02 chamber as a function of depth at (a) 4, (b) 6, (c) 9, and (d) 18 MeV beams. For the NACP-02 chamber, the protocol assumes that the ratio of doses $D_{w}/[D_{air}]_{w}$ is equal to the water-to-air stopping-power ratio, but the dose ratio directly depends on the variation of $P_{wall}$ and $P_{repl}$ values. The dose ratio at a reference depth $d_{ref}$ agrees with the product $(L/P)_{w}P_{wall}$ because the $P_{repl}$ value is close to unity.}
\end{figure}
RZnc code. \([D_{\text{air}}]\) is the dose to the sensitive region in the chamber computed from the \(P_{\text{wall}}\) correction described above. Since \(P_{\text{wall}}\) is equal to unity in Fig. 2, \(P_{\text{repl}}\) is given from Eq. (2) as follows:

\[
P_{\text{repl}} = \frac{D_w / [D_{\text{air}}]_{\text{pp}}}{(L/\rho)^{\text{wall}}_{\text{air}}}. \tag{3}
\]

\((L/\rho)^{\text{wall}}_{\text{air}}\) was calculated using the SPRRZnc code. In recent study, Wang and Rogers \(^{10}\) calculated \(P_{\text{repl}}\) directly with “high density air” (HDA) and “low density water” (LDW) methods against an indirect SPR method [Eq. (3)] used in this study. As the result, it is found that the SPR method is in good agreement with HDA (0.001 mm thickness) and LDW methods. The geometries and materials for plane-parallel chambers used in this study are presented in detail in Table IV of the TRS-398 protocol. For a Markus chamber, a 0.87 mm window mass thickness of NACP-02 is 35% greater than that of Markus and Roos made with PMMA because of its larger atomic number. Recently, Chin et al. \(^{19}\) reported that the front window mass thickness of NACP-02 is 35% greater than that listed in the TRS-398 protocol. This may also increase \(P_{\text{wall}}\). The variation of \(P_{\text{wall}}\) for the plane-parallel chambers reduces with increasing electron energy. For 18 MeV, \(P_{\text{wall}}\) of NACP-02 varies from 1.001 to 1.004 at a depth of 0.2 cm to 1.136 at 1.4 cm for 4 MeV, from 1.004 to 1.079 for Markus and from 1.001 to 1.079 for Roos. NACP-02 composito with graphite and rexolite as a body material shows larger \(P_{\text{wall}}\) values than Markus and Roos made with PMMA because of its larger atomic number. Recently, Chin et al. \(^{19}\) reported that the front window mass thickness of NACP-02 is 35% greater than that listed in the TRS-398 protocol. This may also increase \(P_{\text{wall}}\). The variation of \(P_{\text{wall}}\) for the plane-parallel chambers reduces with increasing electron energy. For 18 MeV, \(P_{\text{wall}}\) of NACP-02 ranges from 1.007 at a depth of 1 cm to 1.023 at 7.45 cm, from 1.002 to 1.023 for Markus and from 1.004 to 1.023 for Roos. The statistical uncertainties of the results computed with CAVRZnc are 0.3%–0.5%, 0.4%–0.6%, and 0.25%–0.4% for NACP-02, Markus and Roos chambers, respectively, which are estimated with quadratic summation of the standard deviation (1σ) in doses for two geometries shown in Fig. 1. The magnitude of the variation in \(P_{\text{wall}}\) with depth for NACP-02 agrees well with results of Buckley and

**IV. RESULTS AND DISCUSSION**

**IV.A. Calculated \(P_{\text{wall}}\) and \(P_{\text{repl}}\)**

Figures 3–5 show several of the factors involved in the dosimetry formalism in TG-51. The dosimetric quantities are calculated as a function of depth within the water phantom for NACP-02, Markus and Roos chambers, at 4, 6, 9, and 18 MeV beams. The depths are varied from near-surface to \(R_{50}\) for each beam. \(P_{\text{wall}}\) increases rapidly as a function of depth at lower energies for all the chambers. \(P_{\text{wall}}\) for NACP-02 varies from 1.004 at a depth of 0.2 cm to 1.136 at 1.4 cm for 4 MeV, from 1.004 to 1.079 for Markus and from 1.001 to 1.079 for Roos. NACP-02 composited with graphite and rexolite as a body material shows larger \(P_{\text{wall}}\) values than Markus and Roos made with PMMA because of its larger atomic number. Recently, Chin et al. \(^{19}\) reported that the front window mass thickness of NACP-02 is 35% greater than that listed in the TRS-398 protocol. This may also increase \(P_{\text{wall}}\). The variation of \(P_{\text{wall}}\) for the plane-parallel chambers reduces with increasing electron energy. For 18 MeV, \(P_{\text{wall}}\) of NACP-02 ranges from 1.007 at a depth of 1 cm to 1.023 at 7.45 cm, from 1.002 to 1.023 for Markus and from 1.004 to 1.023 for Roos. The statistical uncertainties of the results computed with CAVRZnc are 0.3%–0.5%, 0.4%–0.6%, and 0.25%–0.4% for NACP-02, Markus and Roos chambers, respectively, which are estimated with quadratic summation of the standard deviation (1σ) in doses for two geometries shown in Fig. 1. The magnitude of the variation in \(P_{\text{wall}}\) with depth for NACP-02 agrees well with results of Buckley and
The $P_{\text{wall}}$ values different from unity for the plane-parallel chambers is a drastic departure from standard dosimetry theory, especially for lower energy.

The variation of $P_{\text{repl}}$ also increases rapidly as a function of depth at lower energies for all the chambers. $P_{\text{repl}}$ for NACP-02 varies from 0.973 at a depth of 0.2 cm to 1.017 at 1.4 cm for 4 MeV, from 0.938 to 1.172 for Markus and from 0.982 to 1.055 for Roos. The variation of $P_{\text{repl}}$ for Markus is huge compared to NACP-02 and Roos because of the narrow guard ring width. The variation of $P_{\text{repl}}$ for the plane-parallel chambers also reduces as the electron energy increases. For 18 MeV, $P_{\text{repl}}$ of NACP-02 ranges from 0.996 at a depth of 1 cm to 1.017 at 7.45 cm, from 0.992 to 1.022 for Markus and from 1.000 to 1.010 for Roos. The uncertainties of $P_{\text{repl}}$ computed using the DOSRZnrc, CAVRZnrc, and SPRRZnrc codes are 0.3%–0.4%, 0.4%–0.5%, and 0.25%–0.35% for NACP-02, Markus and Roos chambers, respectively. The magnitude of the variation in $P_{\text{repl}}$ with depth for NACP-02 agrees well with results of Wang and Rogers. The standard dosimetry protocols assume that $P_{\text{repl}}$ is equal to unity for well-guarded plane-parallel chambers at all measurement depths. The $P_{\text{repl}}$ values with depth increase drastically at the region with the steep dose gradient for lower energy. For Markus $P_{\text{repl}}$ departs more than 10% from unity close to $R_{50}$. $P_{\text{repl}}$ for NACP-02 and Roos chambers is close to unity in the plateau region of the depth-dose curves.

Figure 6 shows the calculated $P_{\text{wall}}$ values at a reference depth as a function of $R_{50}$ for each chamber and the values are in good agreement with the values reported in previous papers. The $P_{\text{wall}}$ values decrease from 1.019 to 1.008 for NACP-02, from 1.019 to 1.005 for Markus, and from 1.015 to 1.006 for Roos, in a range of 4 MeV ($R_{50}$ =1.31 cm) to 18 MeV ($R_{50}$=7.6 cm). The variation in $P_{\text{wall}}$ with beam quality is approximately 1%.

Figure 7 shows the calculated $P_{\text{repl}}$ values at a reference depth as a function of $R_{50}$ for each chamber. $P_{\text{repl}}$ for well-guarded chambers is close to unity at electron energies greater than or equal to 12 MeV ($R_{50}$=5.06 cm) and consistent with that assumed by standard dosimetry protocols. The variations are larger for low energies, where they are ±0.4% and ±0.5% for the NACP-02 and Roos chambers, respectively. The results for each chamber are in good agreement with those of Wang and Rogers and Zink and Wulff, respectively.

![Figure 5](image1)

**Figure 5.** Calculated dosimetric quantities for a Roos chamber as a function of depth at (a) 4, (b) 6, (c) 9, and (d) 18 MeV beams. For the Roos chamber, the protocol assumes that the ratio of doses $D_p/D_{\text{pp}}$ is equal to the water-to-air stopping-power ratio, but the dose ratio directly depends on the variation of $P_{\text{wall}}$ and $P_{\text{repl}}$ values. The dose ratio at a reference depth $d_{\text{ref}}$ agrees with the product $(L/\rho)_{\text{wall}}P_{\text{wall}}$ because the $P_{\text{repl}}$ value is close to unity.

![Figure 6](image2)

**Figure 6.** Calculated $P_{\text{wall}}$ at a reference depth as a function of $R_{50}$ for NACP-02, Markus, and Roos chambers in a water phantom.
spectively. For Markus, $P_{\text{repl}}$ varies from 0.987 for 4 MeV to 0.995 for 18 MeV. The calculated $P_{\text{repl}}$ values agree within 0.5% with the values recommended by TG-39 (Ref. 18) and TRS-398 that are based on experimental data, except for 4 MeV. The calculated result for 4 MeV is close to our measurement value of 0.983 (Ref. 22) but is approximately 1% larger than the protocols. The measurement for 4 MeV is difficult to perform precisely due to the steep dose gradient and the measurement thus involves a larger uncertainty. The $P_{\text{repl}}$ value for TG-39 and TRS-398 is extrapolated from the regression formula.

### IV.B. Comparison of dosimetric quantities

For the NACP-02 chamber, the standard dosimetry protocols assume that the ratio of doses, $D_{w}/[D_{\text{air}}]_{pp}$, is equal to the water-to-air stopping-power ratio, but the dose ratios directly depend on the variation in the $P_{\text{wall}}$ and $P_{\text{repl}}$ values with depth as shown in Fig. 3. In other words, the ratio of the dose ratio and stopping-power ratio curves corresponds to overall correction factor (the product of $P_{\text{wall}}$ and $P_{\text{repl}}$). The dose ratio almost corresponds to the product $(\bar{L}/\rho)_{\text{air}}P_{\text{wall}}$ with increasing energy, except for a greater depth. The dose ratio at the reference depth also agrees with the product $(\bar{L}/\rho)_{\text{air}}P_{\text{wall}}$ at all beam energies.

For the Markus chamber in Fig. 4, the differences between the dose ratio and stopping-power ratio curves are much larger than those for the NACP-02 chamber because the magnitude of the variation in $P_{\text{repl}}$ with depth is larger. The dose ratio at the reference depth shows better agreement with the stopping-power ratio because the effect of $P_{\text{wall}}$ is cancelled by $P_{\text{repl}}$ correction. The relationship of the dose ratio and the stopping-power ratio for the Roos chamber in Fig. 5 is similar to that for the NACP-02 chamber. The dose ratio at the reference depth is in better agreement with the product $(\bar{L}/\rho)_{\text{air}}P_{\text{wall}}$ than the stopping-power ratio at all beam energies.

The overall correction factor affects significantly depth-dose measurements using the plane-parallel chambers at lower energies. The local dose at $R_{50}$ increases by up to 18% at 4 MeV and 4% at 18 MeV for NACP-02. This is similar to results of Verhaegen et al. Similarly, the dose at $R_{50}$ for Roos increases by up to 11% at 4 MeV and 3.5% at 18 MeV. For Markus the dose increases by up to 21% at 4 MeV and 5% at 18 MeV. However, the dose increment of 18% at $R_{50}$ for 4 MeV increases the depth of $R_{50}$ by only 0.5 mm for NACP-02. The effect becomes smaller with increasing the electron energy.

Figure 8 presents the dose ratio $D_{w}/[D_{\text{air}}]_{pp}$ at the reference depth for NACP-02, Markus and Roos chambers as a function of electron beam quality. The dose ratio for NACP-02 and Roos chambers is shown in comparison to the the results of Verhaegen et al. The effects at electron energies, except for 4 MeV, are smaller than those calculated with the SPRRZnrc code. For Markus the dose ratio is compared with the product of the stopping-power ratio and $P_{\text{repl}}$ recommended by TG-51 and TRS-398.
ratio of TRS-398 at $R_{50}$=1.31 cm. This is in reasonable agreement with the result of Sempau et al.\textsuperscript{5} The overall collection factors for Roos also agree well with results of Zink and Wulff.\textsuperscript{6}

The dose ratio for the Markus chamber increases from 0.5% to 3.3% and from 0.3% to 2.8%, respectively, compared to the values recommended by TG-51 and TG-398, in the range of 4 MeV ($R_{50}$=1.31 cm) to 18 MeV ($R_{50}$ =7.6 cm). The dose ratio at the reference depth for Markus almost agrees with the stopping-power ratio of TG-51 and TRS-398 because the overall correction factor is almost equal to unity as seen in Fig. 4.

V. CONCLUSIONS

This article has investigated $P_{\text{wall}}$ and $P_{\text{repl}}$ correction factors for plane-parallel ionization chambers in clinical electron dosimetry using the EGSnrc Monte Carlo code system. The calculated $P_{\text{wall}}$ values for NACP-02 increase from 1.005 to 1.136 for 4 MeV and from 1.007 to 1.023 for 18 MeV, at a depth between near-surface to $R_{50}$. Similarly, the $P_{\text{wall}}$ values increase from 1.004 to 1.079 and from 1.002 to 1.023 for Markus (that is a classic design), and from 1.001 to 1.079 and from 1.004 to 1.023 for Roos. The $P_{\text{wall}}$ values at a reference depth vary from 1.019 to 1.008 for NACP-02, from 1.019 to 1.005 for Markus, and from 1.015 to 1.006 for Roos, in a range of 4–18 MeV. The calculated $P_{\text{wall}}$ values are different from the value of unity assumed by standard dosimetry protocols.

Also, the calculated $P_{\text{repl}}$ values for NACP-02 increase from 0.973 to 1.079 for 4 MeV and from 0.996 to 1.017 for 18 MeV, at a depth between near-surface to $R_{50}$. Similarly, the $P_{\text{repl}}$ values increase from 0.938 to 1.172 and from 0.992 to 1.022 for Markus, and from 0.982 to 1.055 and from 1.000 to 1.010 for Roos. The $P_{\text{repl}}$ values at the reference depth for NACP-02 and Roos are close to unity in a range of 4–18 MeV. The $P_{\text{repl}}$ values of Markus vary from 0.987 to 0.995 and agree with the values recommended by standard dosimetry protocols except for 4 MeV.

The overall correction factor affects significantly depth-dose measurements using the plane-parallel chambers at lower energies. Although the dose increment around $R_{50}$ for 4 MeV is more than 10%, the effect increases the depth of $R_{50}$ by only 0.5 mm for 4 MeV. The ratio of doses $D_w/D_{\text{air}}$ at the reference depth for NACP-02 and Roos are about 1% larger than the water-to-air stopping-power ratio in the range of 6–18 MeV and 2% larger for 4 MeV. The dose ratio for Markus increases by up to approximately 3% compared to the product of the water-to-air stopping-power ratio and $P_{\text{repl}}$ recommended by TG-51 and TRS-398 for 4 MeV. This study indicates the need for an overall correction factor for the use of plane-parallel chambers in standard dosimetry protocols.

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cation of absorbed doses determined with thimble and parallel-plate ion-
ization chambers in clinical electron beams using ferrous sulphate dosim-
