Determination of Cavity–Gas Calibration and Replacement Correction Factors for Markus Parallel–Plate Ionization Chamber Applied in Electron Beams

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Abstract
The cavity–gas calibration factor \( N_{\text{gas}} \) for a Markus parallel–plate ionization chamber was determined by comparing with a calibrated Farmer chamber using three different calibration methods as recommended in the AAPM's TG–39 protocol. These methods are: (a) high–energy electron beam calibration, (b) photon beam in–phantom calibration, and (c) \(^{60}\)Co in–air calibration. \( N_{\text{gas}} \) with the photon beam in–phantom calibration was determined by \(^{60}\)Co, 4, and 10 MV photons using solid water and MixDp phantoms. The \( N_{\text{gas}} \) values determined by the photon beam in–phantom and \(^{60}\)Co in–air calibrations were about 1% higher than those determined by the high–energy electron beam, while the difference in \( N_{\text{gas}} \) values between the in–air and in–phantom calibrations with a \(^{60}\)Co beam was not observed. The replacement correction factor \( P_{\text{repl,pp}} \) for the Markus chamber was also measured as a function of nominal electron energies from 4 to 15 MeV by comparing with the Farmer chamber whose \( P_{\text{repl,cyl}} \) was obtained from data in the JARP protocol. Resultant \( P_{\text{repl,pp}} \) value decreased in the energy region below 10 MeV.

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1. INTRODUCTION
To determine the absorbed dose in electron beams, especially for energies below 10 MeV, the modern dosimetry protocols recommend the use of parallel–plate ionization chambers.¹–⁵) This is because these chambers have a good depth resolution and a small fluence perturbation effect.
However, a method of calibration, that is, the determination of the cavity–gas calibration factor $N_{gas}$ remains a matter of concern.\textsuperscript{6–13} Several calibration methods have been reported in literature.\textsuperscript{3,14–15} The practical protocols for electron dosimetry with parallel–plate chambers are published by AAPM (1994)\textsuperscript{3}, IPEMB (1996)\textsuperscript{4}, and IAEA (1997)\textsuperscript{5}. In these protocols, the methods to determine $N_{gas}$ are related to one of the following procedures: in–phantom calibration with high–energy electrons, in–air calibration using a $^{60}$Co beam, and in–phantom calibration with a $^{60}$Co beam.

Almost all the protocols recommend as a primary means the calibration of parallel–plate chambers with high–energy electrons at $d_{max}$ in a phantom, intercomparing with a cylindrical chamber whose $N_{gas}$ value has been obtained from a $^{60}$Co beam exposure or air–kerma calibration.\textsuperscript{2–5} As for commercially available parallel–plate chambers, the correction factor to account for the attenuation and scattering and the quotient of absorbed dose by collision kerma $A_{wall}$, as well as the correction factor for composite nature of the chamber wall and buildup cap $K_{comp}$, is not well known in the in–air $^{60}$Co calibration. Also, the correction factor for the chamber wall material different from that of the phantom $P_{wall}$ is not known in the in–phantom $^{60}$Co calibration.

On the other hand, a major source of error in the calibration with high–energy electrons is the perturbation effect introduced by the chamber itself. This effect consists mainly of two origins. The first is the perturbation of the electron fluence due to the introduction of the air cavity with low density into the phantom. This cavity “in–scatter” effect called the replacement correction factor $P_{repl}$ may be an important correction factor if the chambers with 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 $P_{wall}$ mentioned above. In the TG–39 protocol,\textsuperscript{3} $P_{wall}$ is assumed to be unity for electron beams and $P_{repl}$ for several parallel–plate chambers is taken to be unity in mean energy above 15 MeV. Therefore, the in–phantom calibration with high–energy electrons is the only method available to determine $N_{gas}$ of the parallel–plate chambers in which the $K_{comp}$ and $P_{wall}$ values are unreliable.

The purpose of this work is to determine $N_{gas}$ and $P_{repl}$ for a Markus parallel–plate chamber by comparing with a calibrated Farmer cylindrical chamber. Several groups have estimated $N_{gas}$ with several calibration methods for various parallel–plate chambers, and some experimental data have been interpreted as indicating that for some chambers the $N_{gas}$ value may depend on the modality and quality of the beam.\textsuperscript{6–15} In view of such situation, we investigated the dependence of $N_{gas}$ for the Markus chamber on the energy and modality. Also, the Markus chamber has a guard ring with narrow width (0.2 mm) and consequently allows electrons scattering from chamber side walls to enter its active volume. Recent published data\textsuperscript{3–6,8,16–22} indicate that $P_{repl}$ is energy dependent for the Markus chamber, differing considerably from unity at lower electron energies. Hence we will measure $P_{repl}$ as a function of electron energy, and pursue verification of the recently reported results using the Markus chamber.
2. INSTRUMENTS AND METHODS

2.1. Measuring conditions

Schematic diagrams of measuring system are illustrated in Fig. 1. The physical characteristics of the chambers used are listed in Tables 1 and 2. Several groups have used an acrylic phantom matched to the Markus chamber with acrylic walls to produce minimal perturbation in the electron field. In this work, we used solid water (Model 457, RMI — Gammex Inc., Middleton, WI 53562) and MixDp1) phantoms with water equivalence compared to an acrylic phantom. The effective point of measurement for the Farmer chamber was taken at 2/3 of an inner radius proximal to the chamber axis in the in—phantom calibration and at the geometrical center of the chamber in the in—air calibration, while for the Markus chamber it was the inner surface of the entrance window in all the measurements.

The therapy instruments used in this work were the Mitsubishi EXL—15 DP which produced 4 and 10 MV x—ray beams and electron beams from 4—15 MeV, and the Toshiba RCR—120C1 60Co unit. For all charge measurements, the Farmer chamber was used with a Ionex 2500/3 electrometer and the Markus chamber was used with a Victoreen 500 electrometer. The charge measurements were taken with positive and negative polarities, and the average value was used to determine \( N_{gas} \) and \( P_{repl} \). Polarity effect was also studied and the results are described below. The ion recombination correction factor \( P_{ion} \) for the Markus and Farmer chambers was determined by Boag's formula.13 All the measurements required charge ratios between the Markus chamber and the reference Farmer chamber to determine \( N_{gas} \) and \( P_{repl} \). A series of measurements shown in Fig. 1 were repeated at least three times for solid water and MixDp phantoms in different days to make sure that the ratio does not fluctuate by more than 1.0% in day—to—day operation. Also, the

Table 1. Physical characteristics of the cylindrical chamber (Physikalisch—Technische Werkstätten, Freiburg, Germany).

<table>
<thead>
<tr>
<th>Chamber type</th>
<th>Wall Material</th>
<th>Thickness (g cm(^{-3}))</th>
<th>Buildup cap Material</th>
<th>Thickness (g cm(^{-3}))</th>
<th>Inner axial length (mm)</th>
<th>Inner diameter (mm)</th>
<th>( A_{wall} )</th>
<th>( (\bar{u}/\rho)_{wall} )</th>
<th>( N_{gas}/N_{air} )</th>
<th>( (L/\rho)_{wall} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer (PTW 23333)</td>
<td>PMMA</td>
<td>0.059</td>
<td>PMMA</td>
<td>0.530</td>
<td>22.0</td>
<td>6.1</td>
<td>0.992</td>
<td>0.980</td>
<td>8.46×10(^{-3})</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Physical characteristics of the parallel—plate chamber (Physikalisch—Technische Werkstätten, Freiburg, Germany).

<table>
<thead>
<tr>
<th>Chamber type</th>
<th>Entrance window Material</th>
<th>Thickness (mg cm(^{-2}))</th>
<th>Buildup cap Material</th>
<th>Thickness (g cm(^{-3}))</th>
<th>Electrode Diameter (mm)</th>
<th>Electrode Separation (mm)</th>
<th>Guard ring width (mm)</th>
<th>( A_{wall} )</th>
<th>( (\bar{u}/\rho)_{wall} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markus (PTW M23343)</td>
<td>Graphited polystyrene</td>
<td>2.3</td>
<td>PMMA</td>
<td>0.472</td>
<td>5.3</td>
<td>2</td>
<td>0.2</td>
<td>0.994</td>
<td>0.980</td>
</tr>
</tbody>
</table>
2.2. Determination of the cavity-gas calibration factor

(a) Electron beam calibration

A pulsed electron beam with a nominal energy of 15 MeV and with a $15 \times 15$ cm$^2$ field at a source-surface distance of 100 cm was used to irradiate a Farmer chamber of known $N_{gas}$ and the sample Markus chamber. These two chambers were placed in turn in the phantom at $d_{max}$ (dose plateau) and "forced" to receive the same dose [Fig. 1(a)]. $N_{gas}$ for the Markus chamber was obtained from the following relation:

$$N_{gas,pp} = N_{gas,cyl} \left[ M P_{ion} P_{wall} P_{repl} \right]^{pp} / \left[ M P_{ion} P_{wall} P_{repl} \right]^{pp},$$

where $M$ is the measured charge corrected for temperature, pressure, and polarity effect. $P_{repl}$ and $P_{wall}$ are the replacement and wall correction factors. The symbols pp and cyl indicate the parallel-plate and cylindrical chambers, respectively. By the TG–21 protocol, $P_{wall}$ was taken to be unity for electron beams. Also, $P_{repl}$ for the Markus chamber was determined in this work.
while $P_{\text{repl}}$ for the Farmer chamber was obtained from Eq. (A18-1) of the JARP protocol.

All readings were taken after 2.00 Gy irradiation at a dose rate of 4.00 Gy/min with both positive and negative polarities. The average value of $P_{\text{ion}}$ was 1.012 for the Farmer chamber and 1.004 for the Markus chamber, respectively.

(b) Photon beam in-phantom calibration

The Markus and Farmer chambers were positioned in the phantom at a depth of 5.0 g/cm² and exposed to $^{60}\text{Co}$, 4, and 10 MV photons under identical irradiation conditions [Fig. 1(b)]. A 10 × 10 cm² field at a source−detector distance of 100 cm (80 cm for $^{60}\text{Co}$) was used for all irradiations.

$N_{\text{gas,pp}}$ for photon beams can also be determined using Eq. (1). $P_{\text{wall}}$ and $P_{\text{repl}}$ for the Markus chamber were taken to be unity for both solid water and MixDp phantoms. For the Farmer chamber, $P_{\text{repl}}$ was taken to be unity and $P_{\text{wall}}$ was calculated from Eq. (10) of the TG−21 protocol for both phantoms. The values for $\bar{\mu}_{\text{air}}/\rho$ and $\bar{L}/\rho$ were obtained from values of the JARP protocol for MixDp and data of Ho and Paliwal[23] for solid water.

The photon data were read in 1.00 Gy at a dose rate of 1.50 Gy/min for 4 MV, in 1.00 Gy at a dose rate of 3.00 Gy/min for 10 MV, and in 0.65 Gy for a $^{60}\text{Co}$ beam, respectively. The average value of $P_{\text{ion}}$ for both chambers at 4 and 10 MV photons ranged from 1.001 to 1.006.

(c) $^{60}\text{Co}$ in-air calibration

For in-air measurements, the Markus and Farmer chambers were exposed to an equivalent amount of $^{60}\text{Co}$ radiation in air using a 10 × 10 cm² field defined at a source−detector distance of 80 cm [Fig. 1(c)]. A buildup cap thickness for the Markus chamber was 0.472 g/cm² (3 cm in diameter). For the Farmer chamber, the buildup cap thickness was 0.53 g/cm².

From the in-air exposure with the $^{60}\text{Co}$ beam for the Markus and Farmer chambers at the same measuring point, $^{60}\text{Co}$ exposure calibration factor $N_x$ for the Markus chamber is given by

$$N_x = N_{x,\text{cyl}} \left[M_{\text{air,Co}}\right]^{3/2} \left[M_{\text{air,Co}}\right]^{\text{pp}},$$

(2)

where the measured charge is corrected for temperature, pressure, polarity effect, and ion collection efficiency.[1] Therefore, $N_{\text{gas,pp}}$ can be obtained from Eq. (2a) of the TG−39 protocol ($\beta_{\text{wall}}$ is contained in $A_{\text{wall}}$)²⁴ using $N_{x,\text{pp}}$:

$$N_{\text{gas,pp}} = N_{x,\text{pp}} (W/e) A_{\text{ion}} A_{\text{wall}} / \left[(\bar{L}/\rho)_{\text{wall,air}} (\bar{\mu}_{\text{air}}/\rho)_{\text{air,wall}} K_{\text{comp}}\right]^{\text{pp}},$$

(3)

where $W/e$ is the mean energy expended per unit charge in air, $A_{\text{ion}}$ is the ion collection efficiency, $A_{\text{wall}}$ is the correction factor for the attenuation and scattering and the quotient of absorbed dose by collision kerma in the chamber wall and buildup cap, $(\bar{L}/\rho)_{\text{wall,air}}$ is the mean restricted col-
lision mass stopping power ratio for chamber wall to air, \( (\mu_{\text{wall}}/\rho)_{\text{air, wall}} \) is the mean mass energy absorption coefficient ratio for air to chamber wall, and \( K_{\text{comp}} \) is the correction factor for a difference of composite materials between the chamber wall and buildup cap. If the values of \( A_{\text{wall}}/K_{\text{comp}} \) for the parallel-plate chambers are known, \( N_{\text{gas, pp}} \) can be obtained from \( N_{\text{gas, pp}} \) and dosimetric quantities given in the TG-21 protocol. In the present work, we used \( A_{\text{wall}} = 0.994 \) and \( K_{\text{comp}} = 1.000 \) for the Markus chamber according to the JARP protocol.

2.3. Determination of the replacement correction factor in electron beams

\( P_{\text{repl, pp}} \) was obtained from dose comparison between the Markus and Farmer chambers at the depth of \( d_{\text{max}} \) in both solid water and MixDp phantoms. If \( P_{\text{wall}} \) is taken to be unity for all electron beams used in this work, \( P_{\text{repl, pp}} \) can be obtained from the following relation:

\[
P_{\text{repl, pp}} = \frac{[M P_{\text{ion, repl}}^{\text{cyl, E}}/ [M P_{\text{ion}}^{\text{pp, E}}}}{[M P_{\text{ion, repl}}^{\text{cyl, 15E}}/ [M P_{\text{ion}}^{\text{pp, 15E}}}},
\]

where \( P_{\text{repl, 15E}} \) is defined as the value for 15 MeV with the highest electron-beam energy available in this work. The mean electron energy \( \bar{E}_Z \) at depth of 1.5 cm was 10.8 MeV. \( P_{\text{repl, pp, 15E}} \) for the Markus chamber was obtained from Table 2 of the TG-39 protocol, and the interpolated \( P_{\text{repl, pp, 15E}} \) value for \( \bar{E}_Z = 10.8 \) MeV was 0.999.

All of the measurements were made in phantom with a source-surface distance of 100 cm and the effective measuring point for each chamber placed at \( d_{\text{max}} \). A 15 x 15 cm² field defined at the phantom surface was used at nominal electron energies of 4, 6, 9, 12, and 15 MeV. The electron beam parameters given in Table 3 were obtained from measured depth dose curves. Following the JARP and TG-21 protocols, the mean incident energy \( \bar{E}_0 \) was determined by multiplying the depth of 50% dose in water by 2.33 MeV/cm and the mean energy at depth \( \bar{E}_Z \) was obtained from Table A18.2 of the JARP protocol. Also, \( P_{\text{repl, cyl}} \) for \( \bar{E}_Z \) was obtained from Eq. (A18–1) of the JARP protocol. The difference between \( \bar{E}_Z \) obtained from the JARP protocol and the relation \( \bar{E}_Z = \bar{E}_0(1-Z/R_p) \) in the TG-21 protocol does not affect the estimation of \( P_{\text{repl, cyl}} \) (within 0.1%).

All the data were read in 2.00 Gy at a dose rate of 4.00 Gy/min, with both positive and negative polarities. The
average value of $P_{\text{ion}}$ was 1.012 for the Farmer chamber and 1.004 for the Markus chamber, respectively.

3. RESULTS

3.1. Polarity effect

The polarity effect is summarized for the Farmer and Markus chambers in Table 4. The tabulated results are the ratio of the measured charges in positive and negative voltage settings. The Farmer chamber shows the polarity effect in the range of 1.000–1.003 for photons and electron beams in all over the energy range. The effect for the Markus chamber is 1.001–1.003 for all photon energies and 0.997 for electron energies above 12 MeV, but it becomes larger when electron energies are low. It should be noted that the polarity effect for 4 and 6 MeV electron irradiations is no less than 1.3%.

Table 4. Polarity effect measured. The ratios of positive to negative collected charges $M+/M-$ are shown.

<table>
<thead>
<tr>
<th>Nominal energy</th>
<th>Farmer</th>
<th>Markus</th>
</tr>
</thead>
<tbody>
<tr>
<td>±250 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>±350 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Photons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-60</td>
<td>1.003</td>
<td>1.001</td>
</tr>
<tr>
<td>4 MeV</td>
<td>1.003</td>
<td>1.003</td>
</tr>
<tr>
<td>10 MeV</td>
<td>1.003</td>
<td>1.001</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 MeV</td>
<td>1.002</td>
<td>0.987</td>
</tr>
<tr>
<td>6 MeV</td>
<td>1.000</td>
<td>0.987</td>
</tr>
<tr>
<td>9 MeV</td>
<td>1.001</td>
<td>0.992</td>
</tr>
<tr>
<td>12 MeV</td>
<td>1.000</td>
<td>0.997</td>
</tr>
<tr>
<td>15 MeV</td>
<td>1.001</td>
<td>0.997</td>
</tr>
</tbody>
</table>

3.2. Determination of the cavity–gas calibration factor

The results for the determination of $N_{\text{gas,pp}}$ using the above mentioned three calibration procedures are presented in Table 5. The evaluated $P_{\text{wall}}$, $P_{\text{repl}}$, and $P_{\text{ion}}$ values are also shown. The $P_{\text{repl,pp}}$ value at $d_{\text{max}}$ (depth of 2.0 cm) for 15 MeV electrons is 0.997 from the results in Sec.

Table 5. Summary for the evaluated correction factors and $N_{\text{gas,pp}}$ values measured using three different calibration methods.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Depth (cm)</th>
<th>Phantom material</th>
<th>$P_{\text{wall,cvi}}$</th>
<th>$P_{\text{wall,cvi}}$</th>
<th>$P_{\text{wall,se}}$</th>
<th>$P_{\text{ion,se}}$</th>
<th>$P_{\text{ion,pp}}$</th>
<th>$P_{\text{ion,pp}}$</th>
<th>$N_{\text{gas,pp}}$ cGy/nC</th>
<th>Calibration ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-60</td>
<td>5.0</td>
<td>Air</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>48.14±0.09</td>
<td>1.007±0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 MeV</td>
<td>5.0</td>
<td>Solid water</td>
<td>0.996</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>48.14±0.12</td>
<td>1.007±0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MV</td>
<td>5.0</td>
<td>Solid water</td>
<td>0.997</td>
<td>1.000</td>
<td>1.000</td>
<td>1.002</td>
<td>98.20±0.16</td>
<td>1.009±0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 MeV</td>
<td>2.0</td>
<td>Solid water</td>
<td>1.000</td>
<td>0.980</td>
<td>0.997</td>
<td>1.012</td>
<td>47.79±0.17</td>
<td>1.000±0.004</td>
<td></td>
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<tr>
<td><strong>Photons</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-60</td>
<td>5.0</td>
<td>Air</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>48.22±0.22</td>
<td>1.011±0.005</td>
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</tr>
<tr>
<td>4 MeV</td>
<td>5.0</td>
<td>MixDp</td>
<td>1.001</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>48.25±0.27</td>
<td>1.012±0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MV</td>
<td>5.0</td>
<td>MixDp</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.002</td>
<td>98.13±0.36</td>
<td>1.009±0.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 MeV</td>
<td>2.0</td>
<td>MixDp</td>
<td>1.000</td>
<td>0.980</td>
<td>0.997</td>
<td>1.012</td>
<td>47.97±0.21</td>
<td>1.006±0.005</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3. The uncertainties given in Table 5 are the standard deviation for three time measurements. The uncertainties for the ratios in the last column are obtained from the results in each photon beam calibration and the electron beam calibration.

It can be seen in Table 5 that the Markus chamber shows 0.7% — 1.0% higher $N_{\text{gas,pp}}$ values with photon beams than with 15 MeV electrons for solid water phantom, and 0.6% — 1.2% higher $N_{\text{gas,pp}}$ values for MixDp phantom. The dispersion of measured $N_{\text{gas,pp}}$ values for types of the photon beam are within 0.3% and within 0.6% for solid water and MixDp phantoms, respectively. For the $^{60}$Co beam calibration, the $N_{\text{gas,pp}}$ values determined by in-air measurements agree well with those determined by in-phantom measurements.

3.3. Determination of the replacement correction factor in electron beams

The $P_{\text{repl}}$ values measured as a function of electron energy for the Markus chamber are summarized in Table 6. The $P_{\text{repl,pp}}$ values measured in solid water phantom agree with those measured in MixDp phantom within an experimental error.

<table>
<thead>
<tr>
<th>$d_{\text{max}}$ (cm)</th>
<th>$E_{\gamma}$ (MeV)</th>
<th>$E_{\text{z}}$ (MeV)</th>
<th>$P_{\text{repl,cyt}}$</th>
<th>$P_{\text{repl,so}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solid water</td>
<td>MixDp</td>
</tr>
<tr>
<td>1.0</td>
<td>4.3</td>
<td>2.3</td>
<td>0.956</td>
<td>0.973</td>
</tr>
<tr>
<td>1.4</td>
<td>6.3</td>
<td>3.4</td>
<td>0.960</td>
<td>0.988</td>
</tr>
<tr>
<td>2.0</td>
<td>9.4</td>
<td>4.8</td>
<td>0.965</td>
<td>0.990</td>
</tr>
<tr>
<td>2.0</td>
<td>12.3</td>
<td>7.5</td>
<td>0.974</td>
<td>0.996</td>
</tr>
<tr>
<td>2.0</td>
<td>14.6</td>
<td>9.1</td>
<td>0.980</td>
<td>0.997</td>
</tr>
<tr>
<td>1.5</td>
<td>14.6</td>
<td>10.8</td>
<td>0.984</td>
<td>0.999*</td>
</tr>
</tbody>
</table>

*Values interpolated from Table 2 in the TG-39 protocol (Ref. 4)

As expected, $P_{\text{repl,pp}}$ values are very close to 1.0 for 15 and 12 MeV electrons, while they vary considerably at lower energy. The magnitude of variation increases generally as energy decreases, and it deviates by 2.7% at 4 MeV electrons.

4. DISCUSSION

To determine the values of $N_{\text{gas}}$ for the Markus chamber commonly used in electron beams, we observed dispersion of the $N_{\text{gas}}$ values with three calibration methods. Also, an energy dependence of $P_{\text{repl}}$ was found.

4.1. Determination of the cavity—gas calibration factor

The difference of $N_{\text{gas,pp}}$ values obtained by solid water and MixDp phantoms in electron beam calibration is 0.2%, and it is not significant. However, $N_{\text{gas,pp}}$ with the photon beam in—phantom calibration deviates about 1% compared to that with the electron beam calibration in both phan-
To search the origin of the 1% discrepancy, it should be noted that \( N_{\text{gas}, \text{cyl}} \) in Eq. (1) is a constant and is canceled out when the \( N_{\text{gas}, \text{pp}} \) ratio is calculated between photon and electron beams. From repeated charge measurements, we observed uncertainties of 0.2%, 0.2%, and 0.2% for the measured charge, the ion recombination, and the polarity correction factors, respectively. The uncertainties in the charge measurements \( M, P_{\text{pp}} \) are determined to be 0.35% by adding in quadrature the standard deviation of these quantities. Therefore, the discrepancy in \( N_{\text{gas}, \text{pp}} \) may be mainly attributed to the uncertainties in \( P_{\text{wall}} \) and \( P_{\text{repl}} \) in both Farmer and Markus chambers, or combinations of these quantities.

To date, several groups have estimated \( N_{\text{gas}} \) for the Markus chamber and some of the reports show that the \( N_{\text{gas}} \) value is about 1% higher with the photon beam calibration than with the high-energy electron beam calibration.\(^6\) In almost all the calibrations, an acrylic phantom is matched to cylindrical and Markus chambers with acrylic walls to produce minimal perturbation. Our results by the use of solid water and MixDp phantoms are in agreement with their results within the experimental uncertainties. This finding indicates that the differences in \( P_{\text{wall}} \) among the acrylic, solid water, and MixDp phantoms for the Markus chamber are very small.\(^{25-26} \) Here if the uncertainties in \( P_{\text{wall}, \text{cyl}}, P_{\text{repl}, \text{cyl}}, \) and \( P_{\text{repl}, \text{pp}} \) are insignificant, the \( N_{\text{gas}, \text{pp}} \) discrepancy may be caused by the dependence of \( P_{\text{wall}, \text{pp}} \) on the energy and modality of the beam. In this case, \( P_{\text{wall}, \text{pp}} \) corresponds to the ratio of \( N_{\text{gas}, \text{pp}} \) (photon)/\( N_{\text{gas}, \text{pp}} \) (electron) and our results for the Markus chamber agree with the values of \( P_{\text{wall}, \text{pp}} \) for a \( ^{60}\text{Co} \) beam in IAEA-381 protocol\(^5\) within the experimental uncertainties.

On the other hand, in this protocol, the uncertainties in the perturbation factors for the cylindrical and parallel-plate chambers are estimated to be 0.9% in the electron beams and 2.1% in the \( ^{60}\text{Co} \) in-air calibration, respectively. Therefore, the uncertainty in the \( N_{\text{gas}, \text{pp}} \) ratio estimated with both calibrations is 2.3% (1 SD). The 1% difference in the \( N_{\text{gas}, \text{pp}} \) ratio for the Markus chamber is well within this value. However, on the measurements of \( N_{\text{gas}} \) for the parallel-plate chambers, more research are needed to ascertain the magnitude of individual uncertainties.

For the in-air \( ^{60}\text{Co} \) calibration, we have used \( A_{\text{wall}} = 0.994 \) and \( (L/\rho)_{\text{air,wall}} (\bar{\mu}_{\text{ef}}/\rho)_{\text{wall,air}} = 0.980 \) from the JARP protocol for the Markus chamber, while the TG-39 protocol recommends \( A_{\text{wall}} = 1.0030 \) calculated by Rogers.\(^9\) Therefore, the value of \( k_{\text{att}} k_{\text{m}} \) (viz.: \( k_{\text{att}} k_{\text{m}} = A_{\text{wall}}/[(L/\rho)_{\text{wall,air}} (\bar{\mu}_{\text{ef}}/\rho)_{\text{air,wall}} K_{\text{comp}}] \)) used in the IAEA-381 protocol is about 1% lower with the JARP protocol \( k_{\text{att}} k_{\text{m}} = 0.974 \) than with the TG-39 protocol \( k_{\text{att}} k_{\text{m}} = 0.983 \). Latitano\(^{27} \) and Kuchnir and Reft\(^{28} \) have obtained values of \( k_{\text{att}} k_{\text{m}} \) from experimental values, which are 0.988 and 0.976, respectively. These values have a difference within 1% to \( k_{\text{att}} k_{\text{m}} = 0.985 \) estimated with Monte Carlo calculations by Rogers\(^9\). Then, experimental uncertainties in the value of \( k_{\text{m}} k_{\text{att}} \) can be estimated to be about 1%.

Our results with the in-air \( ^{60}\text{Co} \) calibration show about 1% higher \( N_{\text{gas}, \text{pp}} \) values than with the electron beams in both phantoms and are in agreement with the in-phantom \( ^{60}\text{Co} \) calibration. This fact may suggest that \( K_{\text{comp,pp}} \) corresponds to \( P_{\text{wall,pp}} \).\(^6\) However, since the 1% difference is
smaller than the overall uncertainty, no definitive conclusion can be given.

4.2. Determination of the replacement correction factor

For the Markus chamber, $P_{\text{repl,pp}}$ is nearly equal to unity above $E_Z = 10$ MeV. However, the $P_{\text{repl,pp}}$ value decreases with the decrease of the electron energy because the guard ring width is narrow. The $P_{\text{repl,pp}}$ value varies considerably at the low energy of 4 MeV ($E_Z = 2.3$ MeV). The dose plateau at $d_{\text{max}}$ for 4 MeV electrons can be hardly observed. Accordingly, the measured charge at $d_{\text{max}}$ is underestimated because of the relatively large diameter (6.1 mm) of the reference cylindrical chamber and consequently the $P_{\text{repl,pp}}$ value is underestimated. The use of cylindrical chambers, employed as a standard in the measurements of $P_{\text{repl}}$ for parallel-plate chambers, is not recommended in the case of low energies. For the determination of $P_{\text{repl,pp}}$ at low electron energies, it is recommended to make comparisons with ionization chamber dosimetry with extrapolation chambers or Fricke ferrous-sulphate dosimetry. The polarity effect should also be considered in the case of low electron energies.

5. CONCLUSIONS

$N_{\text{gas}}$ for a Markus chamber was determined by comparing with a calibrated Farmer chamber using high-energy photon and electron beams. The photon beam in-phantom and $^{60}$Co in-air calibrations resulted in about 1% higher $N_{\text{gas}}$ values than the electron beam calibration. The origin of the 1% deviation in $N_{\text{gas}}$ may be mainly attributed to the wall effect of the Markus chamber and it remains to be investigated. $P_{\text{repl,pp}}$ for the Markus chamber was also measured as a function of nominal electron energies from 4 to 15 MeV by comparing with the Farmer chamber. The measured $P_{\text{repl,pp}}$ values agreed well with other published data except for 4 MeV electrons case. Therefore, the determination of $N_{\text{gas}}$ for the Markus chamber should be performed with the high-energy electrons above 15 MeV for which $P_{\text{repl,pp}}$ is equal to unity. In the case of $^{60}$Co in-air and photon beam in-phantom calibrations, the respective wall effects of $K_{\text{comp,pp}}$ and $P_{\text{wall,pp}}$ should be taken into consideration.

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