Replacement correction factors for plane-parallel ion chambers in electron beams

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Purpose: Plane-parallel chambers are recommended by dosimetry protocols for measurements in (especially low-energy) electron beams. In dosimetry protocols, the replacement correction factor P_{repl} is assumed unity for "well-guarded" plane-parallel chambers in electron beams when the front face of the cavity is the effective point of measurement. There is experimental evidence that ion chambers which are not well-guarded (e.g., Markus) have nonunity P_{repl} values. Monte Carlo simulations are employed in this study to investigate the replacement correction factors for plane-parallel chambers in electron beams.

Methods: Using previously established Monte Carlo calculation methods, the values of P_{repl} are calculated with high statistical precision for the cavities of a variety of plane-parallel chambers in a water phantom irradiated by various electron beams. The dependences of the values of P_{repl} on the beam quality, phantom depth, as well as the guard ring width are studied.

Results: In the dose fall-off region for low-energy beams, the P_{repl} values are very sensitive to depth. It is found that this is mainly due to the gradient effect, which originates from the fact that the effective point of measurement for many plane-parallel chambers should not be at the front face of the cavity but rather shifted toward the center of the cavity by a fraction of a millimeter. Using the front face of the cavity as the effective point of measurement, the calculated values of P_{repl} at d_{ref} are not unity for some well-guarded plane-parallel chambers. The calculated P_{repl} values for the Roos chamber are close to 1 for all electron beams. The calculation results for the Markus chamber are in good agreement with the measured values.

Conclusions: The appropriate selection of the effective point of measurement for plane-parallel chambers in electron beams is an important issue. If the effective point of measurement is correctly accounted for, the P_{repl} values would be almost independent of depth. Both the guard ring width and the ratio of the collecting volume diameter to the cavity thickness can influence the values of P_{repl}. For a diameter to thickness ratio of 5 (e.g., NACP02 chamber), the guard width has to be 6 mm for the chamber to be considered as well-guarded, i.e., have a P_{repl} value of 1.00. [DOI: 10.1118/1.3276735]

Key words: electron beam dosimetry, plane-parallel ion chambers, replacement correction factors, effective point of measurement, EGSnrc, Monte Carlo

I. INTRODUCTION

For electron beam dosimetry, especially in low-energy beams, plane-parallel chambers are recommended by most dosimetry protocols due to a smaller fluence perturbation effect compared to cylindrical chambers. When the point of measurement for plane-parallel chambers is defined at the front face of the cavity, the gradient effect is believed to be nonexistent. Therefore the replacement correction factor P_{repl} is the same as the fluence correction factor P_{fl} (or p_{cav} in IAEA notation). There were many experiments[1–6] done in the past to measure P_{repl} for some plane-parallel chambers in electron beams; but the results fluctuated as all the measurements had large ($1\sim2\%$) uncertainties. In TG-21 (Ref. 7) and IAEA TRS 277 (Ref. 8) dosimetry protocols, the values of both P_{repl} and the wall correction P_{wall} are taken to be 1 for all plane-parallel chambers at all beam qualities. In TG-39 (Ref. 9) and IAEA TRS 381 (Ref. 10) protocols, nonunity values of P_{repl} for some plane-parallel chambers (e.g., the Markus chamber) were adopted, but P_{wall} was still taken as unity. Currently, both TG-51 (Ref. 11) and IAEA TRS 398 (Ref. 12) dosimetry protocols have assumed unity P_{repl} values for all "well-guarded" plane-parallel chambers. Some recent studies by Monte Carlo simulations[13,14] showed that this might not be true at least for the NACP02 chamber. Zink and Wulff[15,16] studied extensively the perturbation correction factors for Roos chambers in electron beams. Their studies showed that the P_{repl} values for Roos chambers are very close to 1 at the reference depth in all electron beams;[15] it was also suggested that the effective point of measurement for Roos chambers in electron beams should be shifted by 0.04 cm toward the center of the cavity.[16] Similarly we have previously found that for five different plane-parallel chambers, an offset in the effective point of measurement of 0.002–0.045 cm toward the center of the chamber cavity is appropriate.[17] Recent work has shown that the value of P_{wall} in electron beams is not unity for many plane-parallel

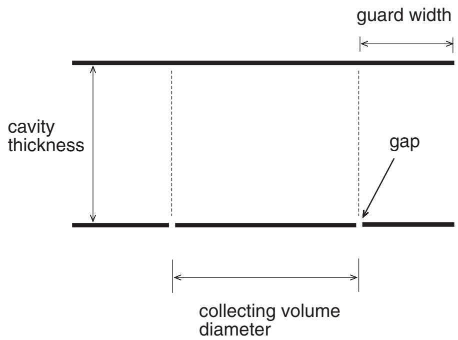

FIG. 1. Collecting volume and guard ring for plane-parallel chambers. The collecting volume is defined by the two vertical dashed lines.

chambers.[18] This complicates matters since it means many measured values of P_{repl} are incorrect since they made use of the assumption that $P_{wall}=1.00$.

In this study, Monte Carlo simulation using EGSnrc[19,20] is employed to study the perturbation effect of cavities for plane-parallel chambers in electron beams. With the previously established methods,[14] P_{repl} is calculated with high precision ($<0.1\%$, 1σ) for a variety of plane-parallel chambers in various electron beams. The effect of the guard ring width on the value of P_{repl} is studied. The results for the Markus chamber are compared to measured values.

II. MATERIALS AND METHODS

II.A. Calculation of P_{repl} for plane-parallel chambers

Figure 1 shows schematically the geometry of the air cavity of a plane-parallel chamber. A guard ring is usually used to define the collecting, i.e., sensitive volume of the chamber and to minimize the leakage current. This is accomplished by separating the collecting electrode into two parts by an insulating gap as shown in the figure. Generally it is suggested by the IAEA (Ref. 10) that the guard ring width should be at least 1.5 times larger than the cavity thickness, and the ratio of the collecting volume diameter to the cavity thickness (diameter to thickness ratio) should be of the order of 10. Table I lists geometrical information concerning the air cavities for the plane-parallel chambers studied here.

The low-density water (LDW) method that we described previously[14] is used to calculate P_{repl} values in this study. For the LDW method, the air in the cavity of a wall-less ion chamber is replaced by a low-density water material which has all the dosimetry characteristics of water except its density is the same as that of air. The ratio of the dose to water in the phantom at the chamber's point of measurement to the dose to the LDW in the cavity will give P_{repl} directly since the stopping-power ratio vanishes as the materials are the same. The cavity is in a water phantom (a cube of 30 cm sides) with its front face at the point of measurement. The dose is scored only in the collecting volume. The radiation source is at 100 cm source-surface distance, 10×10 cm^2 field size, for all the electron beams from 6 to 22 MeV. The spectra of the incident electron beams are from Monte Carlo simulations of a Varian Clinac 2100C linac.[21] A spectrum source from a 22 MeV Elekta SL25 linac electron beam is also used in the calculation. The electron and photon energy thresholds (AE, ECUT and AP, PCUT) are 521 and 10 keV, respectively, since these cutoffs have been shown to give accurate results for LDW calculations.[14]

Calculations of P_{repl} values were done for the five plane-parallel chambers listed in Table I. The depth dependence of the P_{repl} values in the 6 MeV beam and the beam quality dependence of the P_{repl} values at d_{ref} are studied. In addition, the influence of the guard width on the P_{repl} values at d_{ref} in the 6 MeV beam is studied for two series of cavities with the same 10 mm collecting volume diameter, one having a cavity thickness of 2 mm (diameter to thickness ratio is 5) and the other having a cavity thickness of 1 mm (diameter to thickness ratio is 10).

II.B. P_{repl} for Markus chamber

Experimentally it is hard to separate P_{repl} from P_{wall}, so usually their product or the perturbation factor $P=P_{wall}P_{repl}$, is measured. Ding and Cygler[5] did experiments to determine the perturbation factor of a Markus chamber at d_{ref} in a water phantom in various electron beams by comparing its readings to those of an NACP02 chamber. Both the Markus chamber and the NACP02 chamber were cross-calibrated to a cylindrical chamber at d_{max} in a 20 MeV high-energy electron beam. To compare to the experimental data, the perturbation factors for both the Markus and the NACP02 chambers are calculated at d_{ref} in various electron beams from 6 MeV to 22 MeV, and at d_{max} in a 22 MeV high-energy electron beam. Assuming $P_N(Q,z)=[P_{wall}(Q,z)P_{repl}(Q,z)]^{NACP}$ is the NACP02 perturbation factor at depth z in a beam of quality Q, $P_M(Q,z)=[P_{wall}(Q,z)P_{repl}(Q,z)]^{Markus}$ is the perturbation factor for the Markus chamber, and using a derivation similar to that of Ding and Cygler,[5] the following relationship between the perturbation factors and the chamber readings M can be obtained:

TABLE I. The air cavities of several plane-parallel chambers with different guard ring widths (distances in mm).

	Markus	Adv Markus	NACP02	Roos	Attix
Guard width	0.2	2	3	4	13.5
Collecting volume diameter	5.3	5	10	16	12.7
Cavity thickness	2	1	2	2	1
Diameter/thickness	2.6	5	5	8	12.7

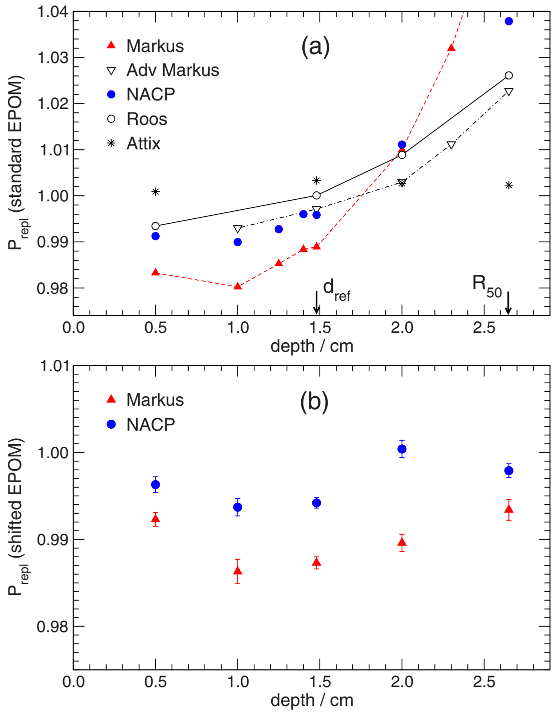

FIG. 2. (a) P_{repl} values of plane-parallel chambers as a function of depth in a 6 MeV electron beam. The front face of the cavity is at the point of measurement. The value for the Markus chamber at R_{50} is off scale at 1.069. (b) The corresponding P_{repl} values for Markus and NACP02 chambers as a function of depth in the 6 MeV electron beam when the point of measurement is shifted toward the center of the cavity by 0.45 and 0.25 mm, respectively (Ref. 17).

$$\frac{P_M(Q,d_{ref})P_N(22,d_{max})}{P_N(Q,d_{ref})P_M(22,d_{max})} = \frac{M_N(Q,d_{ref})M_M(22,d_{max})}{M_M(Q,d_{ref})M_N(22,d_{max})}, \qquad (1)$$

where M_N and M_M are chamber readings for the NACP02 and the Markus chambers, respectively. In their experimental analysis, P_N was assumed to be 1 at both depths and in all the electron beams, and P_M was assumed to be 1 at d_{max} in the 20 MeV beam (in the calculation it is 22 MeV). Under these assumptions, Eq. (1) was used to determine $P_M(Q,d_{ref})$ (i.e., the product of P_{wall} and P_{repl} for the Markus chamber) from chamber readings and their measured value of $P_M(Q,d_{ref})$ is given by the right side of Eq. (1). If one further assumes P_{wall} for the Markus chamber is 1 in all electron beams, as done in current dosimetry protocols, then Eq. (1) gives the measured values of P_{repl} for the Markus chamber. However, as mentioned above, P_{wall} is not unity for these chambers,[18] even in high-energy electron beams. Thus, to verify our calculations, all quantities on the left-hand side of Eq. (1) are calculated in this study and the results are compared to the measurements of the ratio on the right side,[5] thereby avoiding any assumptions about the values of P_{wall}.

III. RESULTS AND DISCUSSION

III.A. P_{repl} vs depth and beam quality

Figure 2(a) shows the calculated P_{repl} values vs depth in the 6 MeV electron beam, for the plane-parallel chambers

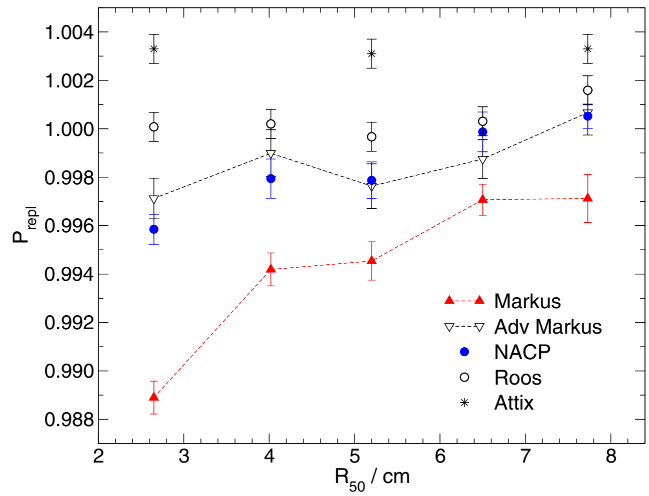

FIG. 3. Beam quality dependence of P_{repl} values at d_{ref} for the five plane-parallel chambers in electron beams.

listed in Table I, when the front face of the cavity is at the point of measurement. The Markus chamber shows a larger a perturbation effect than the other chambers apparently because of its smaller guard width and a small diameter to thickness ratio (see Table I). However, as demonstrated experimentally[22] as well as by our previous study,[17] the effective point of measurement (EPOM) for the Markus chamber in low-energy electron beams should be shifted from the front face toward the center of the air cavity by 0.45 mm.[17] Even for the NACP02 chamber, once thought of as a well-guarded chamber, our study showed a shift of 0.25 mm of the EPOM toward the center of the cavity. Furthermore, the Roos chamber has also been shown to have a shift of 0.18 (Ref. 17) or 0.4 mm (Ref. 16) (the difference between these two values is due to the chamber wall effect, especially the front wall, as we only studied a wall-less Roos chamber[17]). So the large P_{repl} values near R_{50} are likely due to the dose gradient effect, i.e., it might be just an issue of selection of the appropriate EPOM for plane-parallel chambers. When these shifted effective points of measurement are used rather than the front face of the cavity, the calculated P_{repl} values vs depth for the Markus and NACP02 chambers in the 6 MeV beam are shown in Fig. 2(b). The P_{repl} values are almost independent of depth, meaning the gradient effect is largely eliminated. Here the value of P_{repl} at d_{ref} for the Markus chamber is about 0.7% lower than that of the NACP02 due to a smaller guard width and a lower diameter to thickness ratio. The results are consistent with that of the Attix chamber whose P_{repl} value is independent of depth [Fig. 2(a)] and whose EPOM is at the front face of the cavity as we demonstrated earlier.[17] It is interesting to note in Fig. 2(a) that all P_{repl} values, irrespective of type of chamber, appear to be close to 1 at a depth just past d_{ref}, i.e., at about 1.7–1.8 cm in the 6 MeV beam.

Figure 3 shows the beam quality dependence of the P_{repl} values at d_{ref} for these plane-parallel chambers in electron beams when the front face of the cavity is at the point of measurement. The P_{repl} values for the Markus chamber show

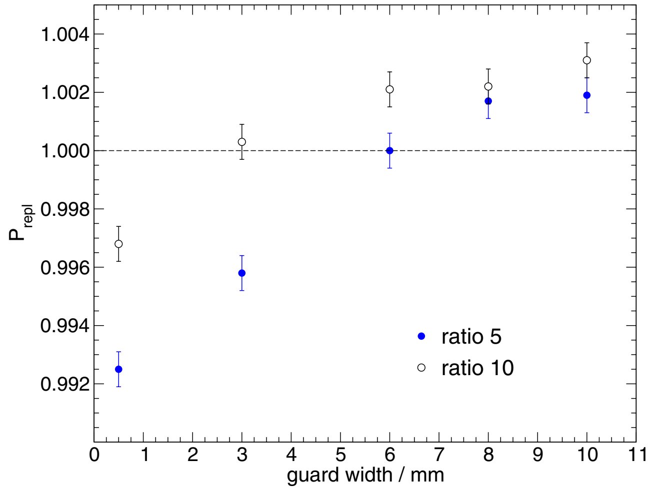

FIG. 4. Calculated P_{repl} values as a function of guard width for plane-parallel chambers with the front of the cavity at d_{ref} in a 6 MeV electron beam. The diameter of the collecting volumes for these chambers is 10 mm. Chambers with two different collecting volume diameter to thickness ratios (5 and 10, 2 mm, and 1 mm cavity thickness, respectively) are studied. A guard width of 3 mm means a cavity diameter of 16 mm.

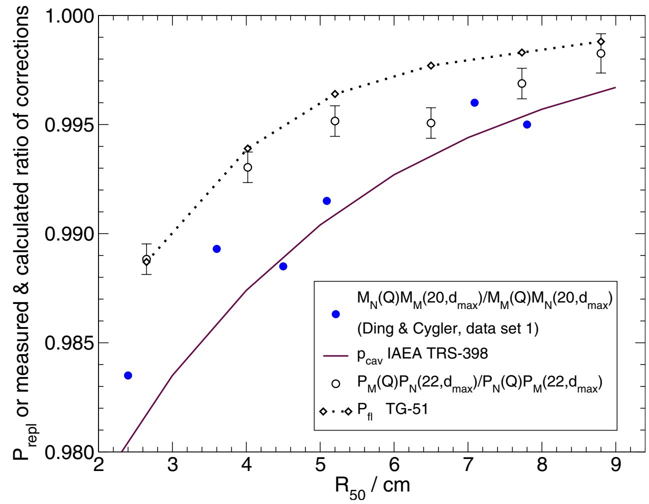

FIG. 5. The calculated ratio of the perturbation factors for Markus and NACP02 chambers in electron beams, i.e., the left side of Eq. (1) (open symbols, uncertainties statistical only) compared to an experimental determination by Ding and Cygler (Ref. 5) of the right side of Eq. (1) (closed symbols, precision about 0.5%). The IAEA and TG-51 data for values for the Markus chamber of p_{cav} and P_{fl}, respectively, are also shown. They are recast from many experimental determinations of the P_{repl} value of the Markus chamber.

a larger variation than other chambers due to its small guard width and small diameter to thickness ratio. The NACP02 chamber behaves similarly to the Advanced Markus chamber since they have the same diameter to thickness ratio of 5 and a similar guard width. The Roos chamber has values of P_{repl} very close to 1 at d_{ref} for all electron beam qualities, which is consistent with the results of Zink and Wulff.[15] The Roos chamber has a diameter to thickness ratio of 8 and a guard width of 4 mm. Both are greater than those of the NACP02 chamber and this makes the Roos chamber guard more effective than that of the NACP02 chamber. For the Attix chamber, the values of P_{repl} are somewhat greater than 1 for all electron beams, suggesting it is "overguarded" due to a very wide guard width.

III.B. P_{repl} vs guard width

Figure 4 shows the calculated P_{repl} values for generic plane-parallel chamber cavities as a function of the guard width for two collecting volume diameter to thickness ratios (5 and 10) for a fixed collecting volume diameter of 10 mm. The front face of the cavity is taken as the point of measurement. The value of P_{repl} is less than 1 for narrow guard rings and it increases with guard width almost linearly until it saturates at a value greater than 1 when the guard is wide enough. A greater-than-one value for P_{repl} means there is a lack of electrons in the collecting volume of the cavity compared to the in-phantom situation because the guard is so wide that the in-scatter effect is diminishing. Figure 4 also tells that for a plane-parallel chamber having a diameter to thickness ratio of 5 (e.g., NACP02), the guard width has to be 6 mm in order to have a unity P_{repl} value in this beam at d_{ref}. For a chamber having a value of 10 for the ratio, as recommended by IAEA TRS-381,[10] a narrower guard width (3 mm) brings the P_{repl} value to unity. Note that the P_{repl} values in Fig. 4 are calculated with the front face of the cavity as the measuring point, but the conclusion is the same if the shifted EPOM is used as the measuring point since the gradient effect is negligible for depths close to d_{max}, which is almost the same as d_{ref} for low-energy electron beams.

III.C. P_{repl} for Markus chamber

When Ding and Cygler[5] measured P_{repl} values for the Markus chamber, its value was given by the right side of Eq. (1). As discussed above, various assumptions in this procedure are now known to be incorrect. Figure 5 compares these measured values, which amount to the right side of Eq. (1) (Ref. 5), to the calculated quantities on the left side of Eq. (1), together with the P_{repl} values used for Markus chamber in TG-51 and TRS-398. The agreement among all the data sets is very good (within 0.5%), keeping in mind that the systematic uncertainty of the LDW method is around 0.1%–0.2% (Ref. 23) and the measurement reproducibility is up to 0.5%.[5]

IV. CONCLUSIONS

Plane-parallel chambers are recommended by dosimetry protocols for measurements in (especially low-energy) electron beams and the effective point of measurement is generally believed to be at the front face of the cavity. Monte Carlo simulation by EGSnrc codes is used to calculate the replacement correction factors (P_{repl}) for some typical plane-parallel chambers in a water phantom irradiated by electron beams. The dependence of the P_{repl} values on the guard ring width as well as the phantom depth and beam qualities for these plane-parallel chambers is investigated. It is found that in the dose fall-off region for low-energy beams, the P_{repl} values are very sensitive to depth. This is mainly due to the gradient effect which originates from the fact that the effective point of measurement for many plane-parallel chambers should not be at the front face of the cavity but rather shifted toward the center of the cavity by a fraction of a millimeter. The effective point of measurement is set at the front face of the cavity to obtain most of the P_{repl} values in this study for the plane-parallel chambers. For the Roos chamber, the P_{repl} values at the reference depth are very close to unity (within 0.2%) in all electron beams, consistent with other studies.[15] For the Markus chamber, the P_{repl} values show larger variation with beam quality than other chambers due to its narrower guard width and smaller diameter to thickness ratio. The calculated ratios of perturbation factors for the Markus and NACP02 chambers agree with experiments within 0.5% and imply that previous measurements of P_{repl} values using such techniques are in error by 0.5% since the reference chamber has nonunity values of P_{repl} and/or P_{wall}. The P_{repl} value for a plane-parallel chamber increases with the guard width until it saturates at a value about 0.2% greater than 1. Both the guard width and the diameter to thickness ratio can influence the values of P_{repl}. For a diameter to thickness ratio of 5 (e.g., NACP02 chamber), the guard width has to be 6 mm for the chamber to be considered as well-guarded.

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