

On the Perturbation Correction Factor p_{cav} of the Markus Parallel-Plate Ion Chamber in Clinical Electron Beams

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Abstract

Purpose: All present dosimetry protocols recommend well-guarded parallel-plate ion chambers for electron dosimetry. For the guard-less Markus chamber, an energy dependent fluence perturbation correction p_{cav} is given. This perturbation correction was experimentally determined by van der Plaetsen by comparison of the read-out of a Markus and a NACP chamber, which was assumed to be “perturbation-free”. Aim of the present study is a Monte Carlo based reiteration of this experiment. **Methods:** Detailed models of four parallel-plate chambers (Roos, Markus, NACP and Advanced Markus) were designed using the Monte Carlo code EGSnrc and placed in a water phantom. For all chambers, the dose to the active volume filled with low density water was calculated for 13 clinical electron spectra ($E_0 = 6 - 21$ MeV) and three energies of an Electra linear accelerator at the depth of maximum and at the reference depth under reference conditions. In all cases, the chamber’s reference point was positioned at the depth of measurement. Moreover, the dose to water D_W was calculated in a small water voxel positioned at the same depth. **Results:** The calculated dose ratio D_{NACP}/D_{Markus} which according to van der Plaetsen reflects the fluence perturbation correction of the Markus chamber, deviates less from unity than the values given by van der Plaetsen, but exhibits similar energy dependence. The same holds for the dose ratios of the other well-guarded chambers. But, in comparison to water, the Markus chamber reveals the smallest overall perturbation correction which is nearly energy independent at both investigated depths. **Conclusion:** The simulations principally confirm the energy dependence of the dose ratio D_{NACP}/D_{Markus} as published by van der Plaetsen. But, as shown by our simulations of the ratio D_W/D_{Markus} the conclusion drawn in all dosimetry protocols is questionable: in contrast to

all well-guarded chambers, the guard-less Markus chamber reveals the smallest overall perturbation correction and also the smallest energy dependence.

Keywords

EGSnrc, Monte Carlo, Cavity Perturbation, Ionization Chamber

1. Introduction

All present dosimetry protocols [1] [2] [3] [4] recommend the use of well-guarded, air-filled parallel-plate ion chambers for reference dosimetry in clinical electron beams. The recommendation of well-guarded chambers is especially based on report 35 of the International Commission on Radiation Units & Measurements (ICRU) [5] which was the principles of clinical electron dosimetry that are summarized. In this report, the so-called *in-scattering effect* is described in detail: based on the strong reduction of the energy losses and multiple scattering of the electrons in the gas-filled cavity compared to the surrounding phantom material, more electrons are scattered into than out of the cavity. As a result, at the lateral boundary of the air-filled cavity, a dose oscillation arises (see Figure (4.2) in ICRU 35) resulting in an over-response of the air-filled cavity, which according to all dosimetry protocols, has to be corrected by a fluence perturbation correction p_{cav} . In attempt to make the chamber signal insensitive to the in/out electrontransport imbalance and thereby, bringing p_{cav} to unity, modern parallel-plate chambers are equipped with a wide guard ring to keep the region of fluence perturbation at a safe distance from the chamber's collecting volume.

Moreover, all present dosimetry protocols assume a negligible influence of the entrance window and the surrounding wall material on the response of modern parallel-plate chambers, *i.e.* the wall perturbation correction defined in all dosimetry protocols is assumed to be unity.

In a previous publication, Zink *et al.* [6] reinvestigated in detail the in- and out-scattering of electrons in gas-filled cavities, which gave a new insight into the perturbation correction p_{cav} for parallel-plate chambers in clinical electron beams. With the help of spatially resolved Monte Carlo calculations, they have shown that the in-scattering effect indeed exists, but they have also shown that a guard ring has only a minor effect on the dose to a gas-filled cavity, especially for cavities with small diameters as in the case of the Markus chamber. The cavity diameter itself has a much larger impact on the dose within the cavity. This is a consequence of the deep radial penetration of the in- and out-bound transport of electrons into the gas-filled cavity. These results question not only the relevance of the guard ring for this chamber type but also the value of the perturbation correction p_{cav} for the guardless Markus chamber given in all present dosimetry protocols. These values are all based on an experimental study performed by Van der Pleatsen *et al.* [7] in the early 1990s. They compared the chamber's

dose D for the guardless Markus chamber with the dose of a NACP chamber in clinical electron beams, assuming that the NACP chamber represents a perturbation-free ion chamber. The ratio $\bar{D}_{NACP}/\bar{D}_{Markus}$ was interpreted as the fluence perturbation correction p_{cav} for the Markus chamber.

The aim of the present study is a Monte Carlo based reiteration of Van der Plaetsen's experiment against the background of the actual knowledge about the in-scattering effect in gas-filled cavities in clinical electron beams. The present data may be especially important regarding the planned update of the international dosimetry protocol IAEA TRS-398 [2].

2. Fundamentals

Following Bragg-Gray theory, the absorbed dose to water D_w may be derived from the dose to the air-filled detector D_{det} the restricted stopping power ratio $S_{w,a}^\Delta$ of the materials water w and air a , and a perturbation correction p [5] [8]:

$$D_w = p \cdot S_{w,a} \cdot D_{det} \tag{1}$$

It is assumed that the perturbation factor p may be factorized, for parallel-plate chambers it is traditionally split into three components:

$$p = p_{wall} \cdot p_{cav} \cdot p_{dis} \tag{2}$$

where p_{wall} stands for the fluence perturbation due to the chamber wall, p_{cav} the in-scattering of electrons from the surrounding phantom material into the air-filled cavity (P_η in The American Association of Physicists in Medicine (AAPM) TG-51 [1]), and p_{dis} for fluence changes due to the replacement of the phantom material water by the air-filled cavity (P_{gr} in AAPM TG-51).

For parallel-plate chambers p_{dis} equals unity according to all present dosimetry protocols when the reference point of the chamber (center of the entrance plane of the air-filled cavity) is positioned at the depth of measurement z . Because of the thin entrance window of all parallel-plate chamber types, also the wall perturbation p_{wall} is assumed to be unity. As the NACP chamber is equipped with a wide guard ring ($w = 0.33$ cm), Van der Plaetsen *et al.* [7] moreover assumed that for this chamber type also p_{cav} is unity for all electron energies, *i.e.* the NACP chamber was considered a perturbation-free ion chamber. Therefore, the dose ratio $\bar{D}_{NACP}/\bar{D}_{Markus}$ is interpreted as the perturbation correction p_{cav} for the Markus chamber due to in-scattering electrons as this chamber type is not equipped with a guard ring of sufficient width ($w = 0.035$ cm). The dose ratio was determined for several primary electron energies at the depth of the dose maximum z_{max} and could be fitted by a function of the mean electron energy $\bar{E}_{z,max}$ at this depth:

$$(p_{cav})_{Markus} = \bar{D}_{NACP}/\bar{D}_{Markus} = 1 - 0.039 \cdot e^{-0.2816 \cdot \bar{E}_{z,max}} \tag{3}$$

In the IAEA protocol [2], this equation was adapted to the actual beam quality specifier R_{50} and the reference depth z_{ref} :

$$(p_{cav})_{Markus} = 1 - 0.037 \cdot e^{-0.279R_{50}} \tag{4}$$

3. Methods and Material

Comparable to the experiments conducted by Van der Plaetsen, the dose ratio $\bar{D}_{\text{det}}/\bar{D}_{\text{Markus}}$ was calculated for the NACP chamber and additionally for the other well-guarded chambers, the Roos and the Advanced Markus chambers, using the Monte Carlo code EGSnrc (V4 2.4.0) [9] [10] [11] [12]. The ion chambers were modeled in detail with the egs++ geometry package according to the blueprints provided by the manufacturer PTW [13]. In the case of the NACP-02 chamber, the geometry is based on the information given in several publications [14]-[19]. Geometric details of the chambers with their material components are summarized in **Table 1** and **Figure 1**. The investigation was performed with thirteen clinical electron spectra ($6 \text{ MeV} < E_0 < 21 \text{ MeV}$) taken from literature [20] and a full modeled Elekta Synergy accelerator including an electron applicator with a field size of $10 \times 10 \text{ cm}^2$ (see **Table 2** for details). For the accelerator model the energies of the primary electrons hitting the scattering foil were $E_0 = 6, 12$ and 18 MeV . The accelerator was modeled with the BEAMnrc code [21] according to the blueprints provided by the manufacturer.

The user code egs_chamber [22] was applied for the calculation of the dose

Table 1. Geometric details of the modeled parallel-plate chambers. V is the active chamber volume, r the radius of the active volume, h its height and w the width of the guard ring. Additionally the entrance window thickness d is given.

Chamber	V	r	h	w	d
	in cm^3	in cm	in cm	in cm	in cm
Roos (PTW-34001)	0.35	0.78	0.2	0.42	0.112
Markus (PTW-23343)	0.055	0.265	0.2	0.035	0.13
Adv. Markus (PTW-34045)	0.020	0.25	0.1	0.2	0.13
NACP-02	0.16	0.5	0.2	0.33	0.06

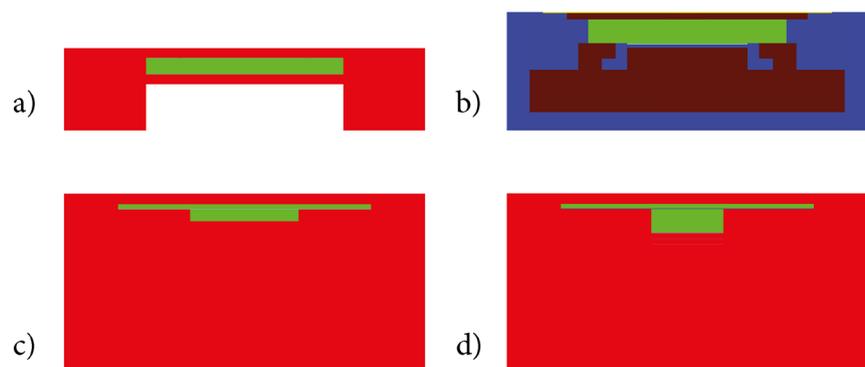


Figure 1. Schematic illustration of the outer dimension and materials of the used parallel-plate chambers: (a) Roos, (b) NACP, (c) Adv. Markus and (d) Markus. The green rectangle represents the air-filled cavity for all chambers. For the Roos, Markus and Adv. Markus the outer material PMMA is given in red. In contrast for die NACP the outer material polystyrene is drafted in blue. The Markus and Adv. Markus chambers have a small air gap above their sensitive cavities. The NACP chamber has inside parts of 1.82 g/cm^3 carbon given in claret.

Table 2. Characteristic data of the electron sources applied in this study. The Elekta Synergy accelerator was modeled in detail including the electron applicator, for the other accelerators only spectra were used as electron sources [19]. The given data are the mean electron energy at the depth of the dose maximum $\bar{E}_{z,max}$ and at the reference depth, the corresponding depths z_{max} and z_{ref} and the electron beam specifier R_{50} .

Linear Accelerator	Nominal Energy	$\bar{E}_{z,max}$	$\bar{E}_{z,ref}$	R_{50}	z_{max}	z_{ref}
Philips SL75-20	5	2.27	2.32	2.11	1.2	1.17
	10	4.22	3.91	4.15	2.2	2.39
	14	7.22	5.35	6.03	2.4	3.52
	17	9.44	6.13	6.96	2.1	4.08
	20	12.5	7.07	8.07	1.6	4.74
Varian Clinac 2100D	6	2.87	2.74	2.65	1.4	1.49
	9	4.13	3.8	4.02	2.1	2.31
	12	5.05	4.68	5.19	2.8	3.02
	15	7.21	5.68	6.5	2.9	3.8
	18	10.17	6.65	7.73	2.5	4.54
Siemens KD2	6	2.37	2.49	2.31	1.35	1.29
	11	3.84	3.96	4.21	2.5	2.43
	21	10.65	7.04	8.3	2.8	4.85
Elekta Synergy	6	2.69	2.69	2.58	1.45	1.45
	12	4.68	4.4	4.84	2.65	2.81
	18	8.38	5.89	7.08	2.8	4.15

deposition \bar{D}_{det} within the detectors and within a small water voxel ($r = 0.5$ cm, $z = 0.02$ cm) to determine the dose to water D_W .

To enable a comparison of the Monte Carlo data with the original data from Van der Plaetsen and with the data given in the IAEA protocol, the simulations were performed for two depths within a water phantom ($30 \times 30 \times 30$ cm³): the depth of the dose maximum z_{max} and the reference depth z_{ref} . In all cases, the chambers were positioned with their reference point at the correspondent depth. The source-to-surface distance was 100 cm and the field size at the phantom surface 10×10 cm². Also to enable comparability with Van der Plaetsen we additionally determined the mean electron energy \bar{E} at the depth of measurement. The determination of the mean electron energies at depth z within the water phantom was performed with the user code FLURZnrc [23]. To calculate the total perturbation correction p the dose to water was also calculated at depths z_{max} and z_{ref} within a small water voxel. To avoid the calculation of the stopping power ratios $s_{w,a}^\Delta$, the cavities of the chambers were filled with low-density water, *i.e.* water with the density of air, and a density correction corresponding to normal-density water [24]. In that case, the perturbation correction p can simply be derived from the dose ratio $\bar{D}_W / \bar{D}_{det}$, *i.e.* $p = \bar{D}_W / \bar{D}_{det}$. The cutoff/threshold energies for the particle transport were set to 512 keV for elec-

trons and 10 keV for photons; all other EGS parameters were set to their default values.

4. Results

Figure 2 shows the ratio of the dose to the active volume of the well-guarded Roos, NACP and Advanced Markus chambers to the dose within the guardless Markus chamber. In the upper panel this dose ratio is given for the depth of the dose maximum z_{max} as a function of the mean electron energy $\bar{E}_{z,max}$, *i.e.* these data are directly comparable with the results published by Van der Plaetsen. The fit according to Equation (3) is additionally shown. As can be seen, the dose for all guarded chambers is quite similar; for all energies they do not deviate from each other by more than 0.3%. For the largest mean energy \bar{E} , corresponding

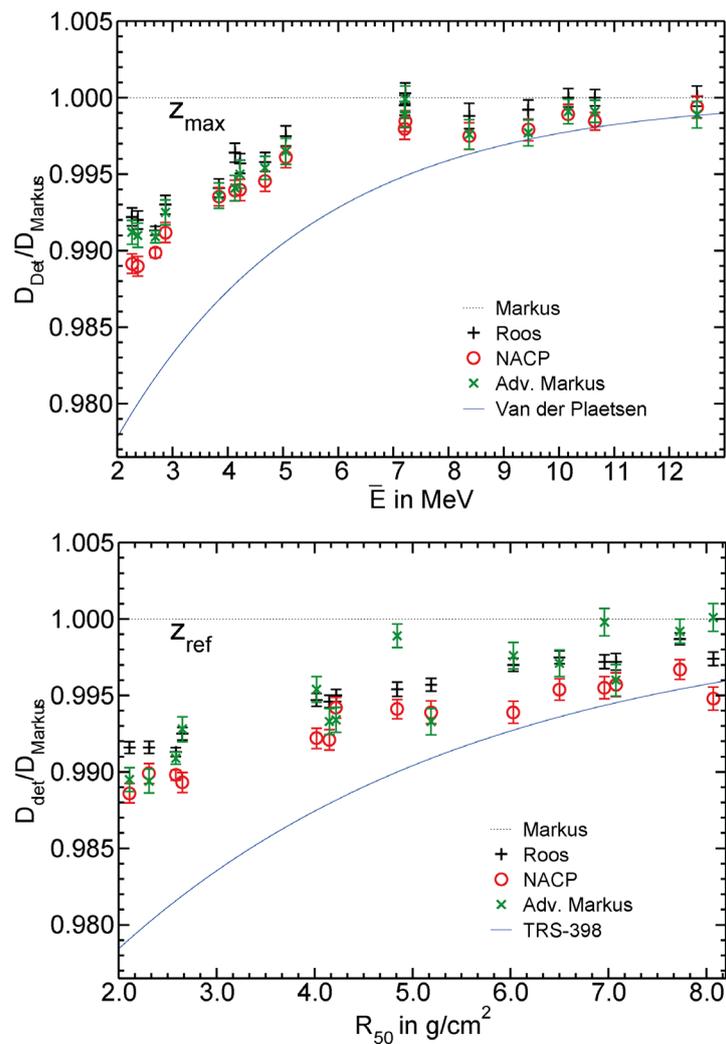


Figure 2. Dose within the active volume of well-guarded parallel-plate chambers (Roos, Adv. Markus, NACP) in relation to the dose within the guardless Markus chamber as a function of the beam quality specifiers and R_{50} respectively. Upper panel: dose ratios at the depth of the dose maximum z_{max} . Lower panel: dose ratios at the reference depth z_{ref} . The solid lines represent the data from Van der Plaetsen and IAEA TRS-398. The error bars indicate the statistical uncertainties of the Monte Carlo simulations (1σ).

to an incident energy of $E_0 = 20$ MeV, the dose ratio $\bar{D}_{\text{det}}/\bar{D}_{\text{Markus}}$ approximately equals unity and decreases for smaller mean electron energies $\bar{E}_{z,\text{max}}$ reaching a value of about 0.99 for the smallest energy investigated here. So, the Monte Carlo based data show an energy dependence similar to the data given by Van der Plaetsen, but the deviations from unity are smaller in comparison to Van der Plaetsen's data.

The data for the reference depth z_{ref} are quite similar with two exceptions: (I) The variation of the dose ratios as a function of the beam quality specifier R_{50} is smaller and even at the highest electron energy the dose ratio is below unity. This is in accordance with the data given in the TRS-398 protocol. (II) The scattering of the Monte Carlo based data points is much larger than for the positioning of the chamber at the maximum depth z_{max} , especially for larger electron energies. This may be an indication that the beam quality specifier R_{50} (and the corresponding reference depth) is not an ideal specifier.

As Van der Plaetsen *et al.* assumed that the NACP chamber is a perturbation-free chamber, the dose ratio $\bar{D}_{\text{NACP}}/\bar{D}_{\text{Markus}}$ was interpreted as the perturbation correction p_{cav} for the guardless Markus chamber (see Equation (3)). To check this interpretation, we also calculated the total perturbation correction $p = D_{\text{W}}/D_{\text{det}}$ for all chambers. These data are given in **Figure 3**.

The total perturbation correction $p = D_{\text{W}}/D_{\text{det}}$ decreases with increasing mean electron energy for the maximum depth z_{max} from about 1.017 to 1.005 for the Roos, NACP and the Adv. Markus chamber. Thus it appears that there is no change of p for energies larger than $E_0 = 12$ MeV (see upper panel). The perturbation correction p of the Markus chamber is smaller than for the other three parallel-plate chambers and varies between 1.001 and 1.005.

For the reference depth z_{ref} the total perturbation factor for the Roos, NACP and the Adv. Markus chamber decreases from about 1.015 to 1.005. In contrast, the perturbation for the guardless Markus chamber is only weakly dependent on energy with a mean value \bar{p} of about 1.003 (see **Figure 3** lower panel).

5. Discussion

The new Monte Carlo results in principle confirm the experimental data from Van der Plaetsen, but the common interpretation of these results may be questionable. According to Van der Plaetsen and also according to all current dosimetry protocols, the dose ratio $D_{\text{NACP}}/D_{\text{Markus}}$ is interpreted as the fluence perturbation correction p_{cav} of the guardless Markus chamber. This interpretation is based on the assumption that the NACP chamber is completely perturbation-free, *i.e.* $p_{\text{wall}} = p_{\text{cav}} = 1$. This assumption may be wrong, as revealed by the calculated total perturbation correction $p = D_{\text{W}}/D_{\text{det}}$ (**Figure 3**).

There have been many experimental [25] [26] [27] [28] [29] as well as Monte Carlo based studies [30] [31] [32] published during the last two decades concerning the perturbation corrections of parallel-plate chambers in clinical electron beams. In all these studies, a wall correction factor $p_{\text{wall}} \neq 1$ for the different parallel-plate chambers was determined. For the NACP chamber, Kuchnir

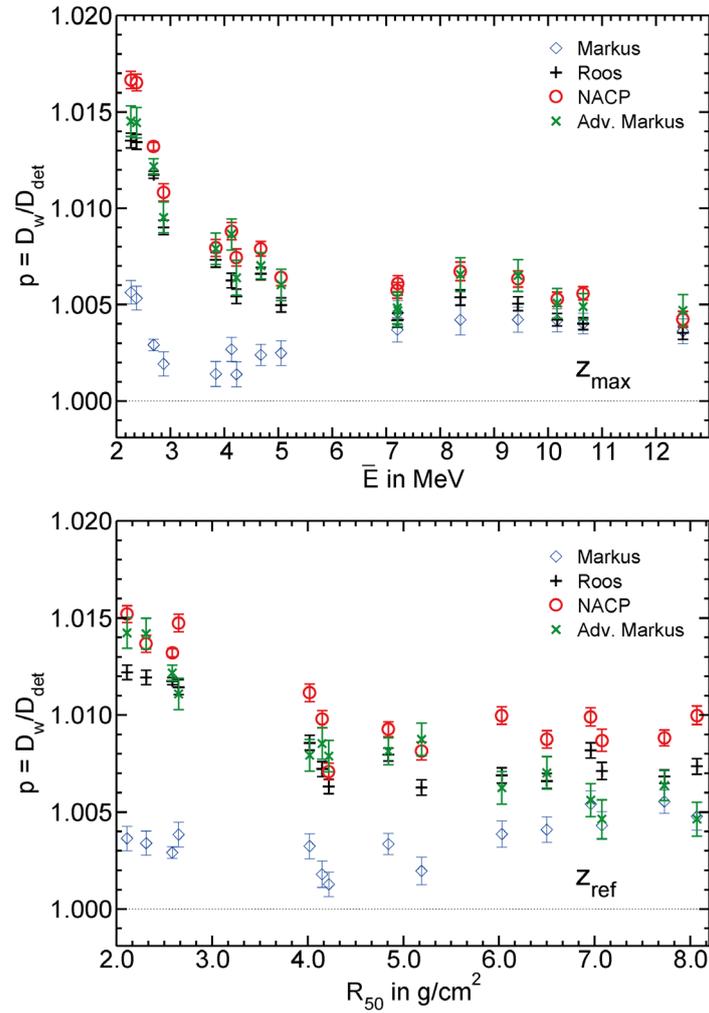


Figure 3. Total perturbation correction p of parallel-plate chambers as a function of the beam quality specifiers $\bar{E}_{z,max}$ and R_{50} . The error bars indicate the statistical uncertainties of the Monte Carlo simulations (1σ).

[33] [34] experimentally determined a wall perturbation correction factor of 1.015 for 4 MeV, 1.006 for 6 MeV and 1.001 for 24 MeV electrons. In more precise measurements, McEwen *et al.* [35] confirmed these results in 2006.

Monte Carlo simulations from Araki [36] also provide a wall perturbation correction p_{wall} for the NACP and Markus chambers from 1.02 for low energies ($R_{50} = 1$ cm) down to 1.005 for high energies ($R_{50} = 8$ cm). Comparable Monte Carlo simulations from our group [18] confirmed these values and gave additional values for the Advanced Markus and Roos chambers, which were also larger than unity. So, as far as we know, the influence of the wall for all parallel-plate ion chambers in clinical electron beams is not negligible, and it is larger than unity.

Regarding the perturbation correction p_{cav} in a previous study [6] with spatially resolved Monte Carlo simulations within cavities comparable to those present in the parallel-plate chambers investigated here, we have shown that there is indeed an in-scattering effect resulting in p_{cav} values smaller than unity

for measuring depths below $R_{50} = 0.5$. As was shown, the increase in dose within air-filled cavities compared to the dose within a water voxel is mainly determined by the cavity radius and not as usually assumed [2] [5] by the guard ring width: the larger the cavity radius, the smaller the impact of in-scattering electrons. Compared to the radius of the air-filled cavity of the Markus chamber ($r = 0.30$ cm), those of the Roos and NACP chambers are quite large ($r = 1.20$ cm and $r = 0.83$ cm including the guard ring, see **Table 1**), *i.e.* the dose increase due to in-scattering of electrons is much more pronounced for the small Markus chamber. Numerical p_{cav} values for the different parallel-plate chambers for the entire clinical energy range have been published by Wang and Rogers [37] as well as by our group [18]. According to these data, large chambers such as the Roos and the NACP chambers reveal p_{cav} values which are near unity for all electron energies. For the small (and guardless) cavity of the Markus chamber, the calculated p_{cav} values were energy-dependent and below unity. For the smallest electron energy investigated in these studies ($R_{50} \approx 2$ cm), p_{cav} deviates by about 1.5% from unity, *i.e.* $p_{cav} = 0.985$.

The radius of the cavity of the Advanced Markus chamber including the guard ring is $r = 0.45$ cm, *i.e.* also much smaller than those of the NACP and the Roos chambers. Therefore, also a non-unity p_{cav} value should be expected. However, in contrast to all other chambers investigated here, the cavity height of the Advanced Markus chamber is only 1 mm, half the value of the other chambers. Due to this small cavity height the in-scattering of electrons into the chamber's cavity is reduced and the p_{cav} value for the Advanced Markus chamber is near unity [18] [37].

As the total perturbation correction p given in **Figure 3** is the product of the above-mentioned factors p_{wall} and p_{cav} an interpretation for the different chambers and different electron energies emerges. For the NACP, Roos and Advanced Markus chambers the total perturbation correction p is determined mainly by the impact of the chamber walls, *i.e.* p_{wall} . The energy dependence of p at the depth of the maximum z_{max} as well as at the reference depth z_{ref} follows that of published p_{wall} data. For the simple Markus chamber the corrections p_{wall} and p_{cav} both deviate from unity, but in opposite directions ($p_{wall} > 1$, $p_{cav} < 1$), therefore, the total perturbation correction p for this chamber remain close to unity and is nearly independent of the energy (see **Figure 3**). Note that strictly speaking our conclusion applies only to the specific depths that were investigated: the reference depth and the depth of dose maximum.

6. Conclusions

In this study, we repeated an old experimental study performed by Van der Plaetsen using Monte Carlo methods. Van der Plaetsen compared a well-guarded NACP chamber and a guardless Markus chamber in clinical electron beams. The non-unity and energy-dependent signal ratio of both chambers was interpreted as the cavity perturbation correction p_{cav} of the Markus chamber. This result was adopted by all common dosimetry protocols, *i.e.* they recom-

mend applying this energy-dependent cavity perturbation correction p_{cav} for the Markus chamber in clinical electron dosimetry.

In our new Monte Carlo calculations, we also compared the signal ratio of different parallel-plate chambers. Additionally, we calculated the perturbation corrections for the different chambers themselves. The results show that the ratio D_{NACP}/D_{Markus} indeed follows an energy dependence similar to the one measured by Van der Plaetsen. However, as the calculation of the perturbation correction p for the different chambers clearly shows, the conclusion drawn by Van der Plaetsen is questionable. Based on the assumption that the NACP chamber is a perturbation-free chamber, he concluded that the ratio D_{NACP}/D_{Markus} corresponds to the cavity perturbation p_{cav} of the guardless Markus chamber. This assumption is according to our own Monte Carlo results which are in good agreement with previous experimental data for the NACP chamber.

Based on our results given in **Figure 3**, it seems likely that the recommendation for the cavity perturbation correction p_{cav} for the Markus chamber given in all current dosimetry protocols is incorrect. Furthermore, the assumption that well-guarded parallel-plate chambers are perturbation-free chambers should be revisited.

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