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A systematic Monte Carlo study of secondary electron fluence perturbation in clinical proton beams (70–250 MeV) for cylindrical and spherical ion chambers

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Current dosimetry protocols for clinical protons do not take into account any secondary electron fluence perturbation in ion chambers. In this work, we performed a systematic study of secondary electron fluence perturbation factors for spherical and cylindrical ion chambers in proton beams (70–250 MeV). The electron fluence perturbation factor, \( p_e \), was calculated using Monte Carlo transport techniques for protons and electrons. The influence of proton energy, cavity wall material (graphite, water, A150, PMMA, polystyrene), cavity radius, cavity wall thickness and positioning depth in water is studied. The influence of inelastic nuclear proton interactions is briefly discussed. It was found that \( p_e \) depends on wall material; the largest values for \( p_e \) were obtained for ion chambers with A150 walls (\( p_e = 1.009 \)), the smallest values for graphite walls. The perturbation factor was found to be largely independent of proton energy. A slight decrease of \( p_e \) with cavity radius was obtained, especially for low energy protons. The wall thickness was found to have no effect on \( p_e \) in the range studied (0.025–0.1 cm). The depth of the cavity in a water phantom was also found to have an insignificant effect on \( p_e \). Based on the results in the paper for spherical and cylindrical ion chambers, a method to calculate \( p_e \) for a thimble ion chamber is presented. The results presented in this paper for cylindrical and spherical ion chambers are in contradiction to the calculated electron fluence perturbation factors for planar ion chambers in the paper by Casnati et al. © 2001 American Association of Physicists in Medicine. [DOI: 10.1118/1.1406519]

Key words: Monte Carlo simulation, protons, electron fluence perturbation in ion chamber walls

I. INTRODUCTION

Insertion of an ion chamber in a water phantom irradiated by a clinical proton beam (50–250 MeV) causes a fluence perturbation for the protons and the secondary electrons. In an air cavity surrounded by a non-air equivalent wall, an imbalance may arise between the energy deposited in the air cavity by electrons that are generated in the wall and the energy deposited in the cavity wall by electrons that originated in the cavity.\(^1\)\(^2\) These perturbations should be accounted for by introduction of a perturbation factor, \( p_Q \), in the proton dosimetry protocols. Current proton dosimetry protocols do not specify any ion chamber perturbation factor.\(^3\)\(^7\) A recent overview can be found in Vatnitsky et al.\(^8\) The ion chamber perturbation factor, \( p_Q \), consists of four contributions:

\[
p_Q = p_{\text{wall}} \cdot p_{\text{cav}} \cdot p_{\text{dis}} \cdot p_{\text{cel}},
\]

where \( p_{\text{wall}} \) corrects for the nonwater equivalence of the cavity wall, \( p_{\text{cav}} \) corrects for the perturbation of the secondary charged particle fluence due to insertion of an air cavity in water, \( p_{\text{dis}} \) represents the displacement correction and \( p_{\text{cel}} \) corrects for the perturbation by the central electrode. The first two factors in Eq. (1) contain the imbalance of the energy deposition in the air cavity and wall by the secondary electrons. Therefore, we can define an electron perturbation factor \( p_e \) which takes this effect into account.

In this work, we studied the electron perturbation factor \( p_e \) for spherical and cylindrical ion chambers by using Monte Carlo transport techniques for protons and electrons. The dependence of \( p_e \) on proton energy, cavity wall material, cavity radius, cavity wall thickness and positioning depth in a water phantom was investigated. Earlier, Casnati et al.\(^1\) used an analytical model to calculate electron perturbation factors for planar geometries and our own group published preliminary results of Monte Carlo simulations for spherical ion chambers.\(^9\) In this paper, the influence of inelastic nuclear proton interactions is briefly discussed and a procedure to apply the calculated results for spherical and cylindrical ion chambers to a thimble ion chamber is outlined. A comparison with measured data was shown in Palmans et al., 2000.\(^10\) The results of our Monte Carlo simulations and measurements for cylindrical and spherical ion chambers will be shown to be in contradiction to the calculated electron fluence perturbation factors for planar ion chambers previously reported.\(^1\)

II. METHODS

The procedure to take into account secondary electrons from protons consists of three steps. Since this has already
been explained in detail in a previous publication\textsuperscript{9} only a brief outline will be given here. In our three-step procedure, first protons from monoenergetic or modulated beams are transported in the geometry shown in Fig. 1. The geometry consists of a spherical or cylindrical ion chamber placed in a water phantom at a certain depth. The chamber has a wall but no central electrode, stem or water proofing sheath. Proton transport is simulated by using the transport code PTRAN,\textsuperscript{11} which was extensively modified by us.\textsuperscript{9,12–14} In the regions indicated in Fig. 1, proton dose and proton fluence spectra are scored. The ion chamber wall materials studied are water, graphite, PMMA, A150, and polystyrene, all with compositions as in ICRU37.\textsuperscript{15} For a water wall, $p_e$ represents $p_{\text{cav},e}$. All materials are used in the same simulation, using a correlated sampling technique.\textsuperscript{9} The incident proton energies used range from 70 MeV to 250 MeV.

In the second step, in the regions shown in Fig. 1, secondary electron generation spectra, differentiated in energy and angle, were calculated by using an analytical approach based on Rutherford proton-free electrons collision theory with a correction, accounting for quantum-mechanical effects, according to Bahba.\textsuperscript{16,17}

Figure 2 shows a graphical representation of an electron spectrum versus electron energy and emission angle with respect to the beam axis, for 70 MeV protons in a 1 mm thick A150 wall of a spherical cavity. The spectra are calculated with a resolution of 1 keV down to a minimum energy of 10 keV. In view of the short range of electrons with energy below 10 keV, at least in the wall materials under investigation, the error introduced by ignoring these electrons was deemed to be very small. To verify this, for a few selected cases, electron spectra with a lowest energy of 1 keV were used in the simulations. The cases studied were 70 MeV and 250 MeV protons for an A150 walled spherical ion chamber (radius 0.25 cm, wall thickness 1 mm). The calculated perturbation factors were found to be within 0.1% of the ones obtained with electron spectra with a lowest energy of 10 keV. Similar results should be obtained for other low-Z materials. This justifies the assumption made above. The average energy of the secondary electrons, not taking the electrons below 10 keV into account, ranges from 28 keV for 70 MeV protons to 40 keV for 250 MeV protons. Figure 2\textsuperscript{a} shows that the number of electrons decreases very strongly with increasing electron energy. Most of the low energy electrons are emitted under large angles with respect to the beam axis [Fig. 2\textsuperscript{b}].

In the final step, electron transport in the geometry of Fig. 1 is performed with the electron transport code EGS4.\textsuperscript{18} In a previous work,\textsuperscript{9} preliminary results for calculations of electron perturbation factors in spherical cavities were given. The obtained perturbation factors for secondary electrons, $p_{e}$, were found to be limited to a maximum correction of 2% but the obtained results showed nonsystematic behavior as a function of primary proton energy. In this work we have implemented several improvements in the electron transport calculations. The improved electron transport algorithm PRESTAI\textsuperscript{19,20} was implemented. In this version of the PRESTA algorithm, some of the inaccuracies in older EGS versions (inaccurate handling of energy loss corrections in the multiple scattering theory, and incorrect implementation
of fictitious cross section method for discrete interactions, are replaced by more accurate implementations. The electron algorithm implemented in the EGS4/PRESTAII code used, is very similar to the one implemented in the more recent code EGSNrc. \textsuperscript{21} We used a double random number sequence in this work; one was used for generating the random numbers for the usual particle transport, a second one was used for the rejection method to sample electrons from the energy/angle differentiated spectra, calculated in the previous step. To improve the efficiency of the electron transport, electron range rejection was used. After random selection of the starting position of an electron in the cavity wall or water shell, its residual CSDA range\textsuperscript{15} was calculated. The electron was then rejected if its distance to the cavity exceeded the conservative value of one and a one-half times its CSDA range. The statistical variances were estimated by splitting up a calculation into 10 batches.

The calculated electron energy depositions were used to correct the calculated proton energy deposition by using

\[ E_{p+e} = E_p + \sum_i (E_{\text{wall},i} - \text{cav} \cdot N_{\text{wall},i}) \]

\[ + \sum_i (E_{\text{water},i} - \text{cav} \cdot N_{\text{water},i}) \]

\[ - E_{\text{cav} - \text{wall}} \cdot N_{\text{cav} - \text{water}} \cdot N_{\text{cav}}, \]

where \( E_{p+e} \) is the average energy deposition in the cavity, taking into account energy deposition by the secondary electrons, \( E_p \) is the average energy deposition per primary proton assuming electron equilibrium exists in the geometry, \( E_{e-b} \) is the average energy per electron generated in region \( a \) and deposited in region \( b \), \( N_q \) is the number of electrons generated in region \( a \) per primary proton and the summations run over the number of subregions in the cavity wall and water shell (see Fig. 1). The electron perturbation factor, \( p_e \), is then calculated as \( p_e = E_p / E_{p+e} \). By defining the electron fluence perturbation factors for the chamber wall and air chamber as follows:

\[ p_{\text{wall},e}^{-1} = 1 + \frac{1}{E_p} \left[ \left( \sum_i E_{\text{wall},i} - \text{cav} \cdot N_{\text{wall},i} \right) - E_{\text{cav} - \text{wall}} \cdot N_{\text{cav}} \right], \]

\[ p_{\text{cav},e}^{-1} = 1 + \frac{1}{E_p} \left[ \left( \sum_i E_{\text{water},i} - \text{cav} \cdot N_{\text{water},i} \right) - E_{\text{cav} - \text{water}} \cdot N_{\text{cav}} \right]. \]

Using the same notations as above, it can be seen that

\[ p_e = p_{\text{wall},e} \cdot p_{\text{cav},e}, \]

since the second order term in the multiplication of Eqs. (3) and (4) will be very small. In principle, the electron perturbation factor could contain a small contribution of the displacement correction factor, \( p_{\text{dis}} \). However, the deviation from unity of this factor will be mainly due to the protons. Also, in view of the fact that the electrons which are generated in the wall and contribute to the energy deposition in the air cavity, are originating from a very thin layer lining the cavity (see Results section), the gradient correction for the secondary electrons must be very small. Certainly, in modulated proton beams, or in the flat dose region near the surface in high-energy proton beams, it will be insignificantly different from unity. In this work, we have assumed that \( p_{\text{dis}} \) for the electrons is vanishingly small, and therefore, \( p_e \) is assumed to consist of \( p_{\text{cav}} \) and \( p_{\text{wall}} \).

To verify the whole procedure, a test with an air cavity (mass density \( 1.205 \times 10^{-3} \text{ g cm}^{-3} \), radius 0.25 cm) surrounded by an air wall with a different density (1.0 g cm\(^{-3}\), thickness 0.1 cm) was performed. Secondary electrons from 100 MeV and 200 MeV protons were transported in this cavity, which was centered at a depth of 10 cm and 20 cm, respectively. For these proton energies at these depths, the total secondary electron fluence in the front and back walls of the cavity differs by no more than \( \approx 1\% \), indicating a homogeneous fluence over the entire cavity. The density effect in the electron energy range and the materials considered in this work, is negligible. Based on Fano's theorem, \textsuperscript{22} the electron fluence perturbation in such a cavity, assuming a fairly uniform proton and secondary fluence over the chamber volume, is expected to be very close to unity. The results confirmed this to be correct to within the statistical uncertainty (\( <0.1\%) \).

Besides studying the electron perturbation as function of energy, wall material and cavity shape (spherical or cylindrical), the wall thickness, the cavity radius and the positioning depth of the cavity was also varied. The depth closest to the surface was at 1.0 cm for 70 MeV and 100 MeV protons, at 1.5 cm for 150 MeV protons and at 2.0 cm for both 200 and 250 MeV protons. In addition, depths of 2.0 and 3.0 cm were used for 70 MeV protons and depths of 22.0 cm and 32.0 cm for 250 MeV protons. For modulated proton beams of 100 MeV and 200 MeV, depths up to 6.5 cm and 23.1 cm, respectively, were investigated. All simulations were performed on an array of 12 Linux PCs (PentiumII&III, clock speeds varying from 300 MHz to 800 MHz). For the calculation of the proton doses and fluence spectra between \( 5 \times 10^6 \) and \( 2 \times 10^8 \) protons were transported depending on the energy, depth and cavity size. The proton transport calculations required between 2 h and 100 h for the five materials. In the cavity \( 5 \times 10^5 \) electrons were sampled, whereas \( 125 \times 10^5 \) electrons were used in the cavity wall and water shell. The most demanding cases (electrons from 250 MeV protons) required calculation times of several days.

In the energy deposited per primary proton, \( E_p \), the fractions attributable to energy deposition due to electronic and nuclear Coulomb interactions and nuclear inelastic interactions were scored. Most data presented in this paper will deal with corrections to the deposited proton energy by electronic and nuclear Coulomb interactions only. Nuclear inelastic interactions become increasingly important at high proton en-
ergies. At 70 MeV, nuclear inelastic interactions increase the proton energy loss by only 10% but this fraction increases to 60% for 250 MeV protons. In water, in regions not too close to the Bragg peak, about 50–70% of the energy lost due to inelastic nuclear interactions is transferred to short-ranged charged particles for which we can assume that their energy deposition is local. This fraction is estimated from a table given by Berger for oxygen. The remainder of the energy loss is transferred mainly to long-ranged neutrons that will not affect the local energy deposition. The effect of taking the nuclear inelastic interactions into account will be briefly discussed.

III. RESULTS AND DISCUSSION
A. $p_e$ versus proton energy for spherical and cylindrical cavities

Figure 3 gives the electron perturbation factor $p_e$ versus effective proton energy at the depth where the cavity is centered. The effective proton energy is calculated from the residual range in water of the protons. The cavity wall thickness is 1 mm in all graphs. For the cylindrical cavities, the cavity height is 1 cm. In almost all cases, the correction factor exceeds unity, i.e., the electrons generated in the walls deposit slightly less energy in the cavity than what is lost by electrons that are generated in the cavity and that exit the cavity. The correction factor is the smallest for graphite walls, the largest for A150 walls. The maximum correction is limited to 0.9%. It has to be remarked that in the case of water, $p_e = p_{cav,e}$ since $p_{wall,e}$ is unity by definition. This factor is also significantly different from unity ($\approx 1.003$). Only for the larger cavity ($R=0.5$ cm) there appears to be a slight increase of $p_e$ with proton energy. For the smaller spherical and cylindrical cavities the increase with proton energy is smaller. The calculated values of $p_e$ for spherical and cylindrical ion chambers of comparable radius are not significantly different in most cases.

For 250 MeV protons, the contribution of electrons that are generated in the water shell surrounding the cavity wall was found to be less than 0.7% of the total energy deposited in the cavity by electrons that are generated outside the cavity. For less energetic protons, this contribution is negligible for a 1 mm wall. Independent of proton energy and cavity radius, it was observed that in spherical cavities roughly two-thirds of the deposited energy by electrons from outside the cavity is coming from electrons that were generated in the front half of the wall. The remainder is coming from the back half. For cylindrical cavities, there is also the contribution of the top and bottom disks to consider (regions 6 in Fig. 1). This was found to increase from about 10% for a cavity radius of 0.125 cm to 30% for 0.5 cm. Correspondingly, the contributions from the front and back halves of the cavity wall decrease, respectively, from about 65% and 25% for $R = 0.125$ cm to 50% and 20% for $R = 0.5$ cm.

The only source available in literature where a comprehensive set of electron perturbation factors is given is the
paper by Casnati et al.\textsuperscript{1} where the authors used an analytical calculation model for the electron fluence perturbation in planar ion chambers. Their results are in contradiction with our results, i.e., they predict a correction of the measured dose in the opposite direction. This can be seen from what the authors termed the inhomogeneity factor tabulated in their Table 2. According to Casnati et al.,\textsuperscript{1} ion chamber readings need to be divided by this factor. Since the values given for this factor all exceed unity for similar materials as in our study, this will result in a correction in the opposite direction from what we found in the present study. Also, the absolute magnitude of the correction factors obtained in the present Monte Carlo study and from the measurements presented in another paper\textsuperscript{10} is about half of the values given by Casnati et al.\textsuperscript{1} Our results indicate that electrons initiated in the air cavity lose more energy to the wall than vice versa. This is in agreement with the early work of Laulainen and Bichsel.\textsuperscript{2} We therefore conclude that the analytical model used by Casnati et al.,\textsuperscript{1} which does not take electron scatter into account properly, is probably too crude to estimate electron fluence perturbations in ion chambers.

For ion chambers with wall materials, other than the ones studied in this work, it is advisable to run additional simulations. However, for low-Z materials, it was found that reasonably reliable interpolation of the calculated perturbation factors can be achieved by using a second order polynomial as a function of the product of the mass density and the atomic number, $\rho Z$. The lower values of $\rho Z$ correspond to the largest perturbation factors.

**B. $p_e$ versus cavity radius for spherical and cylindrical cavities**

The data for $p_e$ given in Fig. 3 is re-plotted in Fig. 4 as a function of cavity radius. For 250 MeV protons there is no significant effect of the cavity radius on the perturbation factor but for lower energies there is a clear decrease of $p_e$ with radius for most cases. In the limit, for very large cavities, eventually the electron perturbation will become insignificant. From Fig. 2 it can be seen that most electrons generated in the cavity wall have an energy of not more than a few tens of keV and consequently, a range of not more than a few mm in air by the time they reach the air cavity. Once the cavity radius exceeds the range of electrons coming from the wall, their deposited dose will no longer increase with increasing radius. Similarly, the relative contribution from electrons from the cavity that deposit their energy in the wall will become less important once certain electrons can no longer reach the wall. In the range of cavity radii that we studied, this effect is expected to be discernible first for the protons with the lowest energy where the electron ranges are the smallest. This is precisely what was observed in Fig. 4 for the lower proton energies.

For the cylindrical cavities the energy deposition of both
from electrons generated in the water shell amounts to about 10% for a wall thickness of 0.025 cm. For lower proton energies the contribution from the electrons from the top and bottom disks, the perturbation should in principle be independent of cavity height. To estimate the influence of the cavity height on the electron perturbation, $p_e$ was calculated for one case; 150 MeV protons and a cylindrical cavity with a radius of 0.25 cm and a wall thickness of 1 mm. Calculations were done for cavity heights of 0.5 cm, 1.0 cm, and 2.0 cm. No significant change in $p_e$ with cavity height was obtained.

**C. $p_e$ versus cavity wall thickness**

The effect of the cavity wall thickness on $p_e$ was studied for a spherical cavity with a radius of 0.25 cm. Simulations were done for 70, 150, and 250 MeV protons. No significant effect of wall thickness on $p_e$ in the range of 0.025–0.1 cm was obtained for any of the proton energies. This is shown in Fig. 5 for 250 MeV protons. The contribution to the energy deposition in the air cavity from the electrons generated in the surrounding water shell by 250 MeV protons increases from an insignificant level for a wall thickness of 0.1 cm to about 10% for a wall thickness of 0.025 cm. For lower proton energies the contribution from the electrons from the water shell is even smaller. For 250 MeV protons we studied a single case for an even thinner wall. With a 0.015 cm thick A150 wall we obtained a 0.1% decrease of $p_e$. For this case, the contribution to the energy deposition in the air cavity from electrons generated in the water shell amounts to about 20%. The slight decrease of $p_e$, bringing its value closer to the one for a water wall, is therefore as expected.

From the above we can conclude that in any realistic ion chamber the contribution to the energy deposited in the air cavity by electrons generated outside the cavity is limited to electrons coming from a thin region of sub-millimeter dimensions lining the cavity wall. We confirmed this further by tallying the distance between the point of generation in the wall and the cavity for electrons that eventually deposit energy in the cavity (spherical cavity radius: 0.25 cm, cavity wall thickness 1 mm). We obtained average distances of about 20 μm in front and back half of the wall for 70 MeV protons and of 180 μm in the front wall and 90 μm in the back wall for 250 MeV protons. The maximum distance from where electrons from the front wall could reach the cavity was found to be 300 μm for 70 MeV protons and 1 mm (i.e., the full wall thickness) for 250 MeV protons. For the back wall the distance was roughly half this value. This is in agreement with our observation for electron generation by protons in high-Z materials. This also means that for the electron perturbations the presence of a waterproofing sheath during measurements in water can be neglected.

**D. $p_e$ for modulated proton beams**

Table I gives electron perturbation factors, $p_e$, for modulated 100 MeV and 200 MeV protons. The dose plateau of the modulated beam extended from a depth of 2.0 cm to 7.4 cm for 100 MeV protons and from 6.5 cm to 25.0 cm for 200 MeV protons. For the simulations a cavity (0.25 cm radius, 0.1 cm wall thickness) was positioned approximately in the middle of the dose plateau. In a modulated beam, the cavity is part of the time exposed to low energy protons in the Bragg peak. This apparently has no large influence since the obtained perturbations are comparable to the values obtained for monoenergetic proton beams (Fig. 3). In principle, the reported values for $p_e$ versus effective proton energy in monoenergetic beams can be used to estimate $p_e$ for a modulated proton beam.

**E. $p_e$ versus depth in modulated and unmodulated proton beams**

For cavities with a radius of 0.25 cm and a wall thickness of 1 mm, consisting of water, graphite, A150, PMMA or polystyrene, the influence of the depth in a water phantom on

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**Table I.** Electron perturbation factor $p_e$ for modulated 100 MeV and 200 MeV protons. The statistical uncertainties (one standard deviation) amount to maximum 0.09% for 100 MeV protons and 0.13% for 200 MeV protons.

<table>
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<th>$E_p$ (MeV)</th>
<th>Depth (cm)</th>
<th>Graphite</th>
<th>Water</th>
<th>A150</th>
<th>PMMA</th>
<th>Polystyrene</th>
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</table>
$p_e$ was investigated. For modulated proton beams of 100 MeV and 200 MeV in the depth ranges of [2.5–6.5 cm] and [7.1–23.1 cm], respectively, no significant effect on $p_e$ was obtained. The same conclusion was reached for a 70 MeV unmodulated proton beam in the depth range (1.0–3.0 cm). For a 250 MeV unmodulated proton beam, no change of $p_e$ in the depth range (2.0–22.0 cm), was obtained. At 32.0 cm depth, a slight increase of $p_e$ by about 0.2% was noted for all wall materials investigated, as can be seen in Fig. 6. This is, however, a statistically insignificant increase. We conclude that the $p_e$ values reported in this work are valid at all positions in the depths ranges mentioned above.

**F. Remarks concerning inelastic nuclear proton interactions**

For high energy protons in water, in addition to the energy transferred to atoms in Coulomb interactions, energy is also transferred in inelastic nuclear interactions. For 250 MeV protons at shallow depths in water, the total energy transfer is increased by 60%. According to Berger in oxygen about 70% of the energy spent in inelastic nuclear interactions by 250 MeV protons is transferred to charged particles for a spherical cavity. For nitrogen, however, this effect of the inelastic nuclear interactions is not known exactly. Therefore, we can only estimate the effect of the inelastic nuclear interactions. It has to be stated that, to our knowledge, the fraction of this energy that is deposited locally in nitrogen is not known exactly. Therefore, we can only estimate the effect of the inelastic nuclear interactions in air by using the data for oxygen, assuming that the fractions for nitrogen are not too different from the ones for oxygen. Based on these assumptions, we found that at shallow depths for 250 MeV protons the perturbation factors for a spherical cavity (radius 0.25 cm, wall thickness 0.1 cm) decrease by 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively. For the same geometry in 100 MeV protons, the perturbation factor decreases by 0.07% for A150 walls and 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively. For the same geometry in 200 MeV protons, the perturbation factor decreases by 0.07% for A150 walls and 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively. For the same geometry in 250 MeV protons, the perturbation factor decreases by 0.07% for A150 walls and 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively. For the same geometry in 300 MeV protons, the perturbation factor decreases by 0.07% for A150 walls and 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively. For the same geometry in 400 MeV protons, the perturbation factor decreases by 0.07% for A150 walls and 0.04%, 0.13%, 0.24%, 0.11%, and 0.20% for graphite, water, A150, PMMA, and polystyrene walls, respectively.

**IV. APPLICATION TO A THIMBLE ION CHAMBER**

Figure 7 shows a schematic representation of a model for a thimble ion chamber with a central electrode. For this type of chamber, the electron perturbation factor, $p_e$, can be obtained by a linear combination of perturbation factors for a cylinder ($p_{e,c}$) and a sphere ($p_{e,s}$) with weighting factors $\gamma_c$ and $\gamma_s$ equal to the respective cavity volume fractions, taking into account the presence of a central electrode. This is a generalization of the model described by Palmans and Verhaegen, where the above expression does not take into account that the central electrode itself may create an additional perturbation of the proton or electron fluence. The perturbation of the proton fluence by a central electrode was reported by us earlier, where it was demonstrated to be very small. The effect of a central electrode on the electron fluence has not been studied in this paper but some information can be gathered from a recent experimental study. Thin central electrodes will cause in most ion chambers a negligible electron fluence perturbation.
V. CONCLUSIONS

In this work, the electron perturbation factor, $p_e$, for spherical and cylindrical ion chambers in 70–250 MeV proton beams was studied. Protons and their secondary electrons were transported in an air cavity in water, including the surrounding cavity wall, using Monte Carlo simulations. The results show that the electron perturbation factor $p_e$ depends on wall material. For ion chambers with graphite walls, values of $p_e$ close to unity were obtained while the largest values were obtained for Al150 walls ($p_e = 1.009$). The electron fluence perturbation factor for a water wall, which is per definition the electron contribution to $p_{cav}$, is also significantly different from unity ($\approx 1.003$). A slight decrease of $p_e$ with cavity radius was obtained, especially for low energy protons. Very similar results were obtained for spherical and cylindrical ion chambers of comparable radius. The perturbation factor was found to show no clear dependence on proton energy in the energy range studied. The wall thickness was found to have no effect on $p_e$ in the range studied (0.025–0.1 cm). This, in combination with the finding that electrons that are generated in the water shell surrounding the ion chamber hardly contribute to the deposited energy in the cavity, indicates that the majority of the electrons capable of entering the air cavity are generated in a very thin layer in the wall. The calculated $p_e$ values for modulated proton beams of 100 MeV and 200 MeV show that these values can be estimated from the $p_e$ values that are reported versus effective proton energy for monoenergetic proton beams. The depth of the cavity in water was found to have an insignificant effect on $p_e$ for 70–250 MeV unmodulated proton beams and for 100–200 MeV modulated proton beams.

The results presented in this paper for electron fluence perturbation for proton beams in cylindrical and spherical ion chambers are in contradiction to results obtained by Casnati et al. for planar ion chambers. As our conclusions are confirmed by experimental results, this could indicate that their analytical model is incorrect.

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Dr. Iwan Kawrakow of NRC, Ottawa is thanked for the use of a pre-release version of the PRESTAIIR electron transport algorithm for the EGS4 Monte Carlo code.


\textsuperscript{1}AAPM Protocol for heavy charged-particle therapy beam dosimetry,” American Association of Physicists in Medicine Report 16 (AAPM, New York, 1986).