Extraction of depth-dependent perturbation factors for parallel-plate chambers in electron beams using a plastic scintillation detector

Frédéric Lacroix^{a)}

Département de Radio-Oncologie, Centre hospitalier de l'Université de Montréal (CHUM), 1560 Sherbrooke Est, Montréal, Québec H2L 4M1, Canada and Département de Physique, Université de Montréal, Pavillon Roger-Gaudry (D-428), 2900 Boul. Édouard-Montpetit, Montréal, Québec H3T 1J4, Canada

Mathieu Guillot

Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, Québec G1K 7P4, Canada and Département de Radio-Oncologie, Hôtel-Dieu de Québec, Centre hospitalier Universitaire de Québec (CHUQ), Québec, Québec G1R 2J6, Canada

Malcolm McEwen and Claudiu Cojocaru

Ionizing Radiation Standards, Institute for National Measurement Standards, National Research Council (NRC), Ottawa, Ontario K1A 0R6, Canada

Luc Gingras

Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, Québec G1K 7P4, Canada and Département de Radio-Oncologie, Hôtel-Dieu de Québec, Centre hospitalier Universitaire de Québec (CHUQ), Québec, Québec G1R 2J6, Canada

A. Sam Beddar

Department of Radiation Physics, Unit 94, The University of Texas M. D. Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, Texas 77030

Luc Beaulieu

Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, Québec G1K 7P4, Canada and Département de Radio-Oncologie, Hôtel-Dieu de Québec, Centre hospitalier Universitaire de Québec (CHUQ), Québec, Québec G1R 2J6, Canada

(Received 15 March 2010; revised 18 June 2010; accepted for publication 22 June 2010; published 28 July 2010)

Purpose: This work presents the experimental extraction of the overall perturbation factor P_Q in megavoltage electron beams for NACP-02 and Roos parallel-plate ionization chambers using a plastic scintillation detector (PSD).

Methods: The authors used a single scanning PSD mounted on a high-precision scanning tank to measure depth-dose curves in 6, 12, and 18 MeV clinical electron beams. The authors also measured depth-dose curves using the NACP-02 and PTW Roos chambers.

Results: The authors found that the perturbation factors for the NACP-02 and Roos chambers increased substantially with depth, especially for low-energy electron beams. The experimental results were in good agreement with the results of Monte Carlo simulations reported by other investigators. The authors also found that using an effective point of measurement (EPOM) placed inside the air cavity reduced the variation of perturbation factors with depth and that the optimal EPOM appears to be energy dependent.

Conclusions: A PSD can be used to experimentally extract perturbation factors for ionization chambers. The dosimetry protocol recommendations indicating that the point of measurement be placed on the inside face of the front window appear to be incorrect for parallel-plate chambers and result in errors in the R_{50} of approximately 0.4 mm at 6 MeV, 1.0 mm at 12 MeV, and 1.2 mm at 18 MeV. © 2010 American Association of Physicists in Medicine. [DOI: 10.1118/1.3463383]

Key words: plastic scintillation detectors, electron beam dosimetry, dosimetry, effective point of measurement

I. INTRODUCTION

All current dosimetry protocols for megavoltage external-beam radiotherapy are based on an absorbed dose-to-water calibration. The absorbed dose is most commonly measured using a calibration coefficient given in terms of absorbed dose to water valid in a ^{60}Co reference beam (obtained from a standards laboratory) and a single k_Q factor is used to con-

vert dose values from the reference beam to the user's beam.¹ National and international protocols discuss a number of different options for obtaining calibration coefficients and k_Q factors. An experimentally determined calibration coefficient for the beam quality of interest is the most direct approach but relies on primary standards of absorbed dose for megavoltage beams and associated calibration services,

something only available in a small number of countries. More generally the approach is to use a chamber-specific ^{60}Co calibration coefficient together with a theoretically derived k_Q factor for a particular chamber type. Such factors are based on water-to-air Spencer–Attix stopping power ratios and values of ion chamber perturbation factors. Perturbation factors account for the nonwater equivalence of the air cavity, wall, electrodes, and stem of the ionization chamber components, as well as for the perturbation of the charged particle fluence caused by the presence of the ion chamber.

For parallel-plate ion chambers, the overall perturbation factor can be separated into three components: (i) A correction for the chamber wall effects, (ii) a correction for the fluence perturbation of the air cavity, and (iii) a gradient correction to account for in-scatter into the air cavity through the chamber sides. All three factors are likely to be functions of incident energy and depth, particularly in electron beams, where the electron spectrum changes noticeably with depth in the phantom.

The location of the effective point of measurement (EPOM) is also required to assign the measured absorbed dose in the chamber volume to a particular point in the undisturbed phantom. A judicious choice of EPOM has been shown to reduce or eliminate one or more of the components of the overall perturbation correction. For example, Tessier and Kawrakow² showed that for photon beams, the correct choice of EPOM means that the perturbation factors when passing from ionization-to-air (the quantity measured) to dose to water are minimized. For practical dosimetry, and particularly for the measurement of depth-dose curves, the use of an EPOM is more practical than the use of perturbation factors, but unfortunately, using the EPOM approach makes the theory of ion chamber dosimetry less intuitive in that a correction to the charge is transferred to a shift in the measurement position. In this context, the EPOM can be considered as a first-order correction when comparing different detectors in the same phantom (e.g., depth-dose curves) or when comparing measurements with the same detector in different materials. The TG-51 protocol uses a “point of measurement” which is similar to the EPOM for parallel-plate chambers but different for cylindrical chambers.¹ Another problem with using the EPOM approach is that it makes it difficult to directly compare experimental results obtained using an EPOM to those obtained from Monte Carlo (MC) simulations. Such simulations now allow all the in-phantom interactions, materials, and physical geometry of the chamber to be accurately simulated and the chamber perturbation factors to be directly calculated.

We focus on parallel-plate chambers as these are usually recommended for electron beam dosimetry. Unfortunately, the various dosimetry protocols have not been consistent in the definition/application of the EPOM for such chambers. Many protocols state that the point of measurement for plane parallel ionization chambers is assumed to be located at the center of the front face (upstream side) of the chamber air cavity. This statement is based on considering the electron fluence for a well-guarded ionization chamber. However, there are varying approaches as to how to deal with the front

window of a parallel-plate chamber, in particular, whether to convert from the physical to a water-equivalent thickness. The TG-51 protocol does not consider the front wall’s water equivalence; however, the IAEA’s TRS-398 code of practice³ recommends that the front wall thickness be scaled to a water-equivalent thickness to determine the EPOM (and therefore the chamber position), but concludes that “this is a very small effect and may be ignored in practice.” In contrast, both the German dosimetry protocol DIN 6800–2 (2008) (Ref. 4) and the U.K. dosimetry code of practice IPEM (2003) (Ref. 5) recommend water-equivalent depth scaling of the front wall for parallel-plate chambers in electron beams. The advantage of depth scaling is that it acts as a first-order correction for the perturbation effect of the chamber front wall, making it simpler to directly compare different models of parallel-plate chambers. For reference dosimetry, the TRS-398 code of practice notes that the difference is not significant as reference measurements are made close to the depth of dose maximum d_{max} , and any difference in the chamber depth between scaling or not scaling the chamber front wall will not change the measured dose significantly. However, if depth-dose curves are measured with different detectors for a low-energy electron beam (e.g., 4 or 6 MeV), then this difference in positioning can be significant.

If the EPOM is defined and the overall perturbation correction at that point is known, then the absorbed dose can be accurately characterized in both absolute and relative terms. The use of an improper EPOM and perturbation factors will lead to errors in the determination of the absorbed dose in electron beams. Before the development of MC simulation-based methods for accurately simulating the full chamber geometry, the overall perturbation correction could only be determined experimentally by comparing the detector in question with a perturbation-free detector. All current protocols conclude that the overall perturbation correction for well-guarded parallel-plate chambers (e.g., NACP-02 and Roos) should be unity; therefore, much of the experimental work published in the literature has used a NACP-02 chamber as the perturbation-free reference chamber to extract the perturbation factors of other ion chambers.^{6–10}

Contrary to the assumptions made in TG-51 and TRS-398, recent experimental data indicate that the NACP-02 chamber cannot be assumed to be perturbation-free. Klevenhagen¹¹ first proposed that the rear wall of the NACP parallel-plate chamber would lead to a non-negligible value of P_{wall} in a water phantom. McEwen *et al.*¹² have reviewed the subject of perturbation factors for parallel-plate chambers and discussed the limits of the experimental methods used to date to measure the P_{wall} values of parallel-plate chambers. Recently, the increase in computing power and the refinement of MC codes have allowed detailed simulations to calculate ion chamber perturbation factors.^{13–19} MC simulations seem to indicate that there are significant perturbation effects for parallel-plate chambers, including the NACP-02 and Roos chambers.

MC simulations have also been used to investigate the validity of the point of measurement recommended by the

current protocols and codes of practice.^{19,20} Wang and Rogers demonstrated that the EPOM is likely shifted inside the air cavity for parallel-plate chambers.¹⁹ Zink and Wulff studied in detail the depth dependence of perturbation factors in electron beam dosimetry for Roos parallel-plate chambers and concluded that taking into account the nonwater equivalence of the front entrance window and placing the EPOM inside the air cavity tended to decrease the variation of perturbation factors with depth.²⁰ One study using thermoluminescent dosimeters indicates that the EPOM is placed inside the air cavity for Roos chambers.²¹

Thus, it is necessary to experimentally investigate the questions raised by these recent numerical investigations in the field of perturbation factors for parallel-plate chambers in electron beam dosimetry. This is what this study aims to do. Direct calibration of ion chambers against a water calorimeter would yield the perturbation factor, although it would be folded in with the water-to-air stopping power ratio. Recently, electron beams with an energy as low as 6 MeV have been measured using a water calorimeter.²² However, there are still issues with operating a water calorimeter in low-energy electron beams.²² Other detectors have been used as perturbation-free references in the determination of perturbation factors. For example, in their study, Reft and Kuchnir used a diamond detector as the perturbation-free reference.⁹ This type of detector would appear to be ideal but the dose-rate dependence of diamond detectors and the uncertainty in diamond stopping powers limit the precision of the data obtained. Other investigators have measured the electron backscatter of various materials and inferred values for the wall perturbation factor P_{wall} of parallel-plate chambers.^{10–12} Ideally, a perturbation-free, water-equivalent dosimeter would be used to provide a benchmark against which to test parallel-plate chambers. Radiochromic films constitute a potential candidate to investigate this issue because of their close water equivalence,^{23–25} but film readout noise issues and film active layer inhomogeneity limit the dosimetric precision that can be achieved using radiochromic films.²⁶ Diodes have been shown to possess valuable characteristics for the measurement of electron beams,²⁷ but there are issues with both dose and dose-rate dependencies and indications that some types of diodes show larger-than-expected effects.²⁸ If the detector being used as a reference requires correction, then it calls into question the result of any comparison with another detector.

Plastic scintillation detectors (PSDs) have evolved substantially in recent years as research has successfully solved the problem of the Cerenkov contamination of the scintillation signal.²⁹ PSDs have been developed for a variety of clinical applications including intensity-modulated radiotherapy quality assurance (QA)^{29–32} and proton beam dosimetry.³³ The close water equivalence of PSDs as well as their real-time response represent attractive characteristics for a dosimeter.^{34,35} Beddar *et al.*³⁶ have recently reviewed the subject of PSDs.

This paper describes the use of a single PSD to extract perturbation factors for parallel-plate chambers (NACP-02 and Roos) in megavoltage electron beams. Depth-dose

curves measured with a PSD were used as a perturbation-free reference to measure ion chamber perturbation factors. In addition to the body of work in the literature on the subject of PSD water equivalence,^{34–36} the minimal fluence perturbation induced by placing a millimeter-sized PSD probe in an electron beam is further established using the CAVITY and DOSRZ EGSnrc MC user codes.

II. METHODS AND MATERIALS

II.A. Extraction of perturbation factors

The Spencer–Attix cavity theory relates the dose to water D_w to the dose in an ideal Spencer–Attix cavity, D_{air}^s , as follows:

$$D_w = D_{\text{air}}^s \left(\frac{\bar{L}_\Delta}{\rho} \right)_{\text{air}}^{\text{water}}, \quad (1)$$

where $(\bar{L}_\Delta/\rho)_{\text{air}}^{\text{water}}$ is the Spencer–Attix water-to-air mean restricted mass collision stopping power ratio with cutoff energy Δ . The overall perturbation factor P_Q is used to relate the dose to the ideal Spencer–Attix cavity D_{air}^s to the dose to an actual ion chamber D_{air} ,

$$D_{\text{air}}^s = D_{\text{air}} P_Q. \quad (2)$$

If an ideal, water-equivalent, perturbation-free detector, such as a PSD, is used, then Eq. (1) can be rewritten as

$$D_w = D_{\text{PSD}} = D_{\text{air}} P_Q \left(\frac{\bar{L}_\Delta}{\rho} \right)_{\text{air}}^{\text{water}}. \quad (3)$$

For parallel-plate ionization chambers, P_Q can be factorized into two components: P_{wall} and P_{repl} , the replacement perturbation factor. P_{repl} can be further factorized into a gradient and a fluence factor,³⁸ so P_Q becomes

$$P_Q = P_{\text{wall}} P_{\text{repl}} = P_{\text{wall}} P_{\text{gr}} P_{\text{fl}}. \quad (4)$$

Note that the equivalent factorization in IAEA TRS-398 notation is $P_{\text{dis}} P_{\text{cav}}$.

P_Q can then be obtained by:

$$P_Q = P_{\text{wall}} P_{\text{repl}} = \frac{D_{\text{PSD}}}{D_{\text{air}} (\bar{L}_\Delta/\rho)_{\text{air}}^{\text{water}}}. \quad (5)$$

In this paper, we used the empirical fit developed by Burns *et al.*³⁹ for the Spencer–Attix water-to-air mean restricted mass collision stopping power ratios. Equation (5) demonstrates that we can determine P_Q for an ion chamber using this method.

When working with percentage depth-dose curves, we normalized the perturbation factors to their value at d_{max} , so we obtained perturbation factors relative to their value at d_{max} , which we termed “relative perturbation factors.” For Eq. (5) to remain valid, “true” water equivalence is not required as long as the mean restricted mass collision stopping power ratio, water/PSD, is constant with energy.

FIG. 1. Schematic diagram of the PSD used in this study.

II.B. PSD

The PSD used in this work is adapted from the system described in Ref. 30. It consists of a 1 mm diameter and 3 mm long scintillating plastic fiber coupled to a clear optical fiber of the same diameter. The scintillating fiber (BCF-12, Saint-Gobain Crystals and Detectors, Paris, France) is a polystyrene core optical fiber in which fluorescent organic molecules are dissolved in a proportion lower than 3% of the weight. The core of the scintillating fiber is surrounded by a 30 μm thick polymethylmethacrylate (PMMA) cladding to guide the scintillation photons through the fiber core by total internal reflection. The mass density and electronic density, respectively, are 1.05 g/cm^3 and 3.40×10^{23} electrons/ cm^3 for the scintillating plastic fiber as compared to 1.00 g/cm^3 and 3.34×10^{23} electrons/ cm^3 for water. The clear optical fiber used is a PMMA resin core surrounded by a 10 μm thick fluorinated polymer cladding. The PSD is encapsulated in a 0.6 mm thick opaque polyethylene jacket to shield the detector from external light sources. Figure 1 presents a schematic diagram of the PSD used in this study.

The light output of the PSD is composed of scintillation photons that are proportional to the energy deposited in the scintillator volume and Cerenkov light, which is a contamination signal related to the electron energy fluence in the optical fiber. The light exiting the PSD is measured by using a polychrome red-green-blue charge-coupled device (CCD) camera, and the blue and green channels are used to spectrally deconvolve both signals and relate the dose measured by the PSD to the scintillation signal.²⁹ No other correction factor is applied to the PSD response. The CCD camera was cooled to -20°C , and each measurement was repeated five times to increase the precision of the PSD measurements. Figure 2 presents the polystyrene-to-water mass collision stopping power ratio as a function of energy (www.nist.gov). The variation in stopping power is about 1.5% from 10 keV to 30 MeV. In the megavoltage energy range, the variation in stopping power is 0.5% from 1 to 20 MeV.

FIG. 2. Polystyrene-to-water mass collision stopping power ratio as a function of energy.

II.C. MC simulations of the PSD in electron beams to verify its water equivalence

The first step is to demonstrate that the PSD can be considered a perturbation-free detector. As described in Sec. II B, the PSD was constructed from materials that are almost water-equivalent, which when combined with the PSD's small physical size, suggests that the PSD has a negligible perturbation effect in electron beams.

To verify this, we used the National Research Council (NRC) of Canada Vickers research linac beam model to numerically benchmark the water equivalence of the PSD. This beam model was selected because of its simple and well-characterized treatment head geometry. The advantage of using this geometry is that there are no free parameters in the simulation (energy, spot size, and beam divergence are known). The BEAMnrc software was used to simulate the setup of the NRC's Vickers linac.⁴⁰ In this model, the monoenergetic electron beam travels through a vacuum, impinges on the accelerator exit window, then travels through the air, is slightly scattered by thin aluminum foils, and then travels through the air until it reaches the water tank. The BEAMnrc model is then used as a shared library by two EGSnrc user codes to calculate the depth-dose curves in water. The scoring of absorbed dose in the water tank at various depths was simulated using the DOSRZnrc EGSnrc user code, while the dose in the PSD was calculated using the CAVITY EGSnrc user code. The following EGSnrc radiation transport parameters were used in this work: Electron lower energy cutoffs (ECUT and AE) of 0.521 MeV and photon lower energy cutoffs (PCUT and AP) of 10 keV.

Simulations were performed for beam energies of 6, 9, 13, and 20 MeV to cover the energy range of interest in this numerical investigation. The exit window of the Vickers linac is composed of 0.0043 cm of titanium. For the 9 and 13 MeV beams, 0.052 cm of aluminum were added; for the 20 MeV beams, 0.101 cm of aluminum were added; for the 6 MeV beams, however, no additional scattering material was added. In addition, simulations were performed of a 20 MeV

beam using a 5 mm thick aluminum foil to simulate the response of the PSD in a beam containing a sizable fraction of Bremsstrahlung photons.

II.D. NRC scanning tank and positioning of the NACP-02 and Roos chambers

An in-house system previously described by McEwen *et al.*⁴¹ was used for the depth-dose measurements. Briefly, this portable system was constructed based on a $30 \times 30 \times 30$ cm³ PMMA water phantom with a thin entrance window (11 cm $\times$ 11 cm $\times$ 1.8 mm). A precision mechanical stand-off combined with a telescope mounted at the side of the water phantom was used to set the origin for the scans. The absolute reproducibility of probe positioning is estimated to be better than 0.1 mm.⁴¹

The parallel-plate chambers were positioned according to the NRC's current protocol. Scaling of the front wall of each chamber is used with the EPOM of the NACP-02 chamber taken to be 1.0 mm below the outer surface of the front window and that of the Roos chamber is taken to be 1.15 mm. Note that distances will be referenced to the outer surface of the front window in the rest of the paper. However, recent data indicate that the physical construction of the NACP-02 and Roos chambers might not correspond to these values.⁴² This will be discussed in detail in Sec. IV.

II.E. Measurements using a clinical beam

Measurements were performed at the CHUQ in clinical electron beams produced by a Varian Clinac 21iX linac (Varian Associates Inc., Palo Alto, CA). Beam energies of 6, 12, and 18 MeV were used at a setting of 400 MU/min. A 10×10 cm² applicator was used with an applicator mask, yielding a 10×10 cm² field at a source-to-surface distance of 100 cm. A field chamber was positioned in the corner of the radiation field where any scatter effect on the in-phantom detector was minimal to correct the scanning data for any variations in dose rate. The ion chamber signals (scanning and reference chamber) were measured using two Keithley 6517A electrometers and the complete system was under computer control.

The scanning protocol was a "step and collect" technique: The detector (i.e., the NACP-02 chamber, Roos chamber, or the PSD) was moved to a specific position and then a 5–10 s charge integration was carried out. A single scan involved movement in both directions to monitor any hysteresis or short-term linac instability. Multiple scans were obtained for each detector and measurements were made on several days to check repeatability. The same scanning protocol was used for both chamber and PSD measurements. For the parallel-plate chambers, since a scan could take several minutes (worst-case scenario) to complete, all measurements were corrected for temperature and pressure. For the PSDs, however, no corrections for temperature and pressure were performed.^{34,35}

FIG. 3. 6, 9, 13, and 20 MeV depth-dose curves (top) and dose difference curves (bottom) calculated using the CAVITY and DOSRZ EGSnrc user codes for a thin aluminum windows (see Sec. II C). "Water" indicates that the calculation was done in the water tank. "PSD" indicates that the calculation was done in the PSD.

III. RESULTS

III.A. MC simulations

Figure 3 shows the depth-dose curves of MC simulations for dose to water and dose to the PSD in an electron beam produced by the Vickers linac. Difference plots between the dose to water and the dose to the PSD are also shown. The standard deviation on the MC simulations was 0.5% at $d_{\max}$.

As shown in the difference plots in Fig. 3, there is no statistically significant differences between the depth-dose curves calculated in water and those calculated in the PSD within the simulation uncertainty accounting for error propagation in the difference curves (0.7%).

Simulations were also performed in a 20 MeV electron beam produced by the Vickers linac using a 5 mm thick aluminum scattering foil to produce a sizable Bremsstrahlung component as present in a clinical beam. Again, there were no significant differences between the depth-dose curves calculated in water and those calculated in the PSD for all depths beyond the $d_{\max}$ within the simulation uncertainty. However, there was a slight difference of up to 0.5% in the first few points of the buildup up to about the 1 cm depth. This difference was largest close to the water surface which indicates that it might be due to a slight over-response

FIG. 4. Depth-ionization curves for the 12 MeV beam obtained using the Roos chamber (circles) and the NACP-02 chamber (crosses). The inset plot shows the relative difference in local ionization (solid circles). The second data set (diamonds) shows the effect of a 0.15 mm shift in the positioning of the NACP-02 chamber relative to that of the Roos chamber. Data for the 6 and 18 MeV beams were similar (not shown).

of the PSD to low-energy photons. However, for the results presented in this work, we are concerned with measurements made away from the water surface where no such discrepancy was observed.

III.B. Measurements using a clinical beam

III.B.1. Depth-dose measurements using the NACP-02 and Roos chambers

To determine the relative perturbation factors for these parallel-plate chambers, we must accurately compare the depth-dose curves obtained using them. First, we must demonstrate that we can obtain the required positioning accuracy. Figure 4 shows the percentage depth-ionization curves for the 12 MeV beam produced by the CHUQ Varian linac obtained using the Roos and NACP-02 chambers. The level of agreement is typical of the data acquired during this investigation and in a range of beams at the NRC laboratories in Ottawa. With scaling for water-equivalent thickness of the chamber window (as discussed in Sec. II D), we typically see positioning differences at the level of 0.1–0.15 mm. These differences are generally in the same direction, which indicates either (i) a bias in setting the reference position within the water phantom or (ii) an error in the thickness of the chamber window (see Sec. IV). Comparisons have also been carried out using the NRC linacs between chambers of the same type (i.e., two NACP or two Roos chambers) and agreement was also obtained at the level of 0.1 mm. These positioning differences are approaching the precision limits of the positioning system and setup protocol. Figure 4 also indicates that if uncertainties in the relative perturbation cor-

FIG. 5. Depth-dose curves obtained using the NACP-02 chamber and the PSD in 6, 12, and 18 MeV beams produced by the CHUQ Varian linac. The NACP-02 chamber data was converted to dose using Burns *et al.*'s nine-parameter equation. The EPOM of the NACP-02 chamber was taken to be 1.0 mm below the surface of the front window. All plots are individually normalized to $d_{\max}$.

rections at the 1% level are desired, then the whole depth-dose curve cannot be used. The data are certainly valid up to the depth of R_{50} , but beyond this depth, the small signal and steep dose gradient mean that even positioning differences of 0.1 mm become significant.

III.B.2. Depth-dose measurements using the NACP-02 chamber and the PSD

Figure 5 shows the percentage depth-dose curves for the 6-, 12-, and 18 MeV beams measured using the PSD and the NACP-02 chamber. Difference curves between the NACP-02 and PSD are also shown (—). The uncertainty (one standard deviation) on the PSD measurement was equal to 0.7% at $d_{\max}$. The uncertainty on the NACP-02 measurement was smaller than 0.1%. The EPOM for the NACP-02 was placed 1.0 mm below the surface of the front window in accordance with standard practice at NRC.

It is perhaps not obvious in Fig. 5 but there is a systematic trend with the dose measured by the PSD being higher than the dose measured by the NACP and this difference increases with depth. The PSD produces a slightly larger value for R_{50} than the NACP-02 chamber at 12 and 18 MeV. The differences are approximately 0 mm at 6 MeV, 0.6 mm at 12 MeV, and 0.8 mm at 18 MeV when the EPOM of the NACP-02 chamber was placed at 1.0 mm below the surface of the front window (or 0.4 mm inside the air cavity). When using the 0.6 mm EPOM suggested by the TG-51 protocol, the differences in R_{50} as measured by the PSD and the NACP-02 chamber were 0.4, 1.0, and 1.2 mm at 6, 12, and 18 MeV, respectively.

III.C. Extraction of relative perturbation factors

Using the procedure outlined in Sec. II A, we calculated P_Q . The perturbation factors indicate the departure of the ion

FIG. 6. Relative perturbation factors as a function of depth for the NACP-02 chamber at 6 MeV for a 0.6 and 1.0 mm EPOM. MC simulation data points reported by Buckley *et al.* (Ref. 16), Araki (Ref. 17), and Chin *et al.* (Ref. 18) are shown for comparison. The uncertainty bars shown are one sigma and include the combined PSD and NACP-02 chamber measurement uncertainties.

chamber depth doses from the ideal perturbation-free behavior (taken from the PSD). The uncertainty in the relative perturbation correction was estimated to be 0.85% around $d_{\max}$ and at R_{50} and 3% around the practical range R_p . There is more variation with depth because of the decrease in both the PSD and chamber signals.

III.C.1. NACP-02 chamber at 6, 12, and 18 MeV

Figure 6 shows the relative perturbation factors as a function of depth for the NACP-02 chamber for 6 MeV. Two EPOMs are shown: 0.6 and 1.0 mm. The 0.6 mm EPOM corresponds to the physical thickness of the NACP-02 chamber front window and is the EPOM commonly used in MC simulations in accordance with the TG-51 recommendations (more on this in Sec. IV).

Data points taken from Refs. 16–18 modeling NACP chambers in various 6 MeV beams (not necessarily of the same quality as the CHUQ electron beams used in this work) are included for comparison. References 16–18 use an EPOM located at 0.6 mm depth with respect to the surface of the chamber. All data points were normalized at $d_{\max}$. Chin *et al.*¹⁸ used beams of almost identical quality to the CHUQ electron beams that we used (within 0.05 MeV), but Buckley *et al.*¹⁶ used beams with a slightly higher quality (by 0.2 MeV at 6 and 12 MeV and 0.1 MeV at 18 MeV) and Araki¹⁷ used beams with a slightly lower quality at 6 MeV (0.25 MeV less) and the same quality at 18 MeV. Unfortunately, Buckley *et al.*¹⁶ do not provide perturbation factors as a function of depth for 12 and 18 MeV and Araki¹⁷ does not provide data for 12 MeV. Overall, such small differences in beam quality should have little impact on the relative perturbation factors.

Figure 6 shows that there is a good agreement between

FIG. 7. Relative perturbation factors as a function of depth for the NACP-02 chamber at 12 MeV for a 0.6 and 1.0 mm EPOM. MC simulation data points taken from Chin *et al.* (Ref. 17) are also shown.

the relative perturbation factors calculated for a 0.6 mm EPOM and the relative perturbation factors taken from Refs. 16–18.

Figure 6 also shows that using a 1.0 mm EPOM flattens out the relative perturbation factors over the whole depth-dose curve as far as R_p , which suggests that the chamber perturbation factors might be able to be expressed in terms of a fixed EPOM and a single scaling factor (to convert the relative perturbation factors obtained here to absolute factors required for dosimetry protocols). Tessier and Kawrakow² successfully used this approach for thimble ion chambers in megavoltage photon beams. The choice of EPOM has little effect on the buildup portion of the depth-dose curve, as expected, and Fig. 6 indicates a slight 1%–2% discrepancy between the PSD and the NACP-02 in the buildup region.

Figure 7 shows the relative perturbation factors as a function of depth for the NACP-02 chamber for 12 MeV. MC simulation data points reported by Chin *et al.*¹⁸ are included for comparison.

The Chin *et al.*¹⁸ data agreed better with our data at 12 MeV than at 6 MeV. Again, using an EPOM larger than the simple physical thickness, placed in the air cavity, decreased the variation in the relative perturbation factors with depth.

Figure 8 shows the relative perturbation factors as a function of depth for the NACP-02 chamber for 18 MeV. MC simulation data points reported by Araki¹⁷ and Chin *et al.*¹⁸ are shown for comparison.

At 18 MeV, both experimental curves (EPOM=0.6 mm, EPOM=1.0 mm) provide relative perturbation factors that are slightly larger at R_{50} than the MC simulations, although the match is not inconsistent with the uncertainties.

III.C.2. Roos chamber at 6, 12, and 18 MeV

Figure 9 shows the relative perturbation factors as a function of depth for the Roos chamber for 6 MeV. Two EPOMs are shown: 1.0 and 1.15 mm. The 1.0 mm EPOM corresponds to what is commonly assumed to be the physical

FIG. 8. Relative perturbation factors as a function of depth for the NACP-02 chamber at 18 MeV for a 0.6 and 1.0 mm EPOM. MC simulation data points reported by Araki (Ref. 17) and Chin *et al.* (Ref. 18) are also shown.

thickness of the Roos chamber front window and the 1.15 mm EPOM is the NRC EPOM for the Roos chamber (more on this in Sec. V).

Figure 9 shows that the trends for the Roos chamber data are identical to those for the NACP-02 chamber data: There was good agreement between MC data and measurements when an EPOM of 1.0 mm was used, but placing the EPOM inside the air cavity reduced the variation in the relative perturbation factors with depth. The disagreement between measurements and MC simulations amounted to a positioning error of 0.1 mm. This method of determining relative perturbation factors is only possible because of the high accuracy with which the ion chamber and PSD can be placed in the water phantom.

Figure 10 shows the relative perturbation factors as a function of depth for the Roos chamber for 12 MeV.

Unfortunately, no simulation data are available for comparison at 12 MeV for the Roos chamber, but the available Roos chamber data are consistent with the NACP-02 data in

FIG. 9. Relative perturbation factors as a function of depth for the Roos chamber at 6 MeV for 1.0 and 1.15 mm EPOM. MC simulation data points reported by Araki (Ref. 17) are also shown.

FIG. 10. Relative perturbation factors as a function of depth for the Roos chamber at 12 MeV for a 1.0 and 1.15 mm EPOM.

that scaling for the water-equivalent thickness of the front window does not result in a relative perturbation factor that is independent of depth.

Figure 11 shows the relative perturbation factors as a function of depth for the Roos chamber 18 MeV. The Roos chamber data are similar to the NACP-02 chamber data with the measurements showing a larger perturbation correction at R_{50} than the calculated results.

IV. DISCUSSION

This work has focused on the characterization of electron beams with a PSD and parallel-plate chambers using a high-precision measurement setup. We extracted depth-dependent relative perturbation factors and compared them to Monte Carlo simulations published in the literature. The perturbation factors indicate the departure of the ion chambers from an ideal Spencer–Attix cavity. As previously mentioned, the overall perturbation factor P_Q is the product of the wall perturbation factor P_{wall} and the replacement perturbation factor P_{repl} . In this experiment, we could not separate these factors

FIG. 11. Relative perturbation factors as a function of depth for the Roos chamber at 18 MeV for a 1.0 and 1.15 mm EPOM. MC simulation data points reported by Araki (Ref. 17) and Chin *et al.* (Ref. 18) are also shown.

because we did not have a set of chambers with very specific differences in construction which is required to identify the relative importance of the wall and cavity effects. However, by demonstrating that the MC results are valid, we established that MC simulations can confidently be used to investigate these two components.

We used a single PSD to successfully extract relative perturbation factors for two types of parallel-plate chambers. The fact that perturbation factors were extracted with an acceptable (0.7%) uncertainty indicates how far PSD technology has evolved in recent years to the point that it is now fit for dosimetric investigations requiring water-equivalent detectors. The PSD system that was used was designed for beam QA using multiple detectors;³⁰ it was not optimized as a single scanning detector. The one sigma uncertainty on the PSD measurement of 0.7% at $d_{\max}$ could be substantially reduced by optimizing the PSD system.^{43,44} In particular, optimizing the system's light collection efficiency and software automation would also substantially decrease the time needed to perform a scan using a PSD (Ref. 44) as the CCD integration time is a function of the light collection efficiency. Note that a distinction must be made between the PSD used in this study which has undergone thorough validation^{30,33–35,37,43,44} and which is constructed entirely of water-equivalent materials and other designs of plastic scintillator-based dose detectors that use nonwater-equivalent materials such as silica, air, and/or silver, which yields electron depth-dose curves with substantial differences (more than 1%) from either MC or ionization chambers.^{45,46}

A direct comparison of the PSD response with MC simulations of a linac beam could also be performed. For a clinical linac, this requires very accurate modeling of all the system components, which is presently a challenging task.⁴⁷ A linac with a well-defined energy and geometry, such as the NRC Vickers linac, could be used for this type of work. At the level of precision that we are working at (better than 0.1 mm), the linac beam energy needs to be controlled to better than 0.02 MeV, which is equivalent to a 0.3% energy stability at 6 MeV and 0.1% at 18 MeV, which is very difficult to obtain.⁴⁸

Figures 6–11 show that there was a good agreement between the PSD measurements and MC simulation results of NACP-02 and Roos chambers reported by various authors. These figures also show that there is a small (1%–2%) difference in the buildup between the PSD and the ion chambers. Note that this difference is also present in the MC simulation data.

All the MC calculations used the geometrical thickness of the front wall, ignoring any nonwater material; therefore, the best agreement would be expected when the experimental data used the same EPOM. The “MC tuned chamber” refers to an NACP-02 chamber where the physical thickness of the front window is 35% greater than the manufacturer's specifications, while the “sacrificed chamber” refers to an NACP-02 chamber where the front window is 35% more dense, not 35% thicker, than previously thought.¹⁸ In contrast, Buckley *et al.*¹⁶ and Araki¹⁷ assumed standard front window thickness and density in their MC simulations. The

slightly better match to the Buckley *et al.* and the Araki simulations in Fig. 6 close to R_{50} is surprising as it would be expected that taking into account a 35% density or thickness difference in MC simulations would provide a better fit to our experimental data and thus that the Chin *et al.* data would be closer to the experimental values. This raises the following questions: Is our NACP-02 chamber identical to the sacrificed chamber or MC tuned chamber used by Chin *et al.*, i.e., is the front window thicker or denser than the manufacturer's specifications? Have the chamber construction details changed with time? The drawing supplied with the chamber used in this investigation (SN 75–10) is consistent with the MC model of Chin *et al.*, but McEwen *et al.*⁴⁶ showed using radiographs that a small change in the NACP-02 chamber design (not reflected in the drawings supplied with each chamber) was correlated with a significant change in chamber response (volume). In addition, some design changes cannot be detected using radiographs. For example, it would be very difficult to detect a change in the graphite density of the NACP-02 front window. The only reliable option, as Chin *et al.* carried out, is to dismantle, i.e., destroy, the chamber.

Although only relative perturbation factors are presented, they constitute an important step in validating the use of MC simulations to calculate absolute perturbation factors. The variation in perturbation factors seen for any single depth-dose curve is larger than the absolute perturbation corrections reported in the literature at depths of interest (e.g., $d_{\max}$ and z_{ref}). However, as pointed out by Chin *et al.*, MC results can only be as good as the construction data provided by the manufacturers.⁴² Another issue is that manufacturers provide nominal specifications for each ion chamber model that do not take into account fabrication tolerances and possible material composition variability. Therefore, two ion chambers of the same model from the same manufacturer could give different responses.⁴⁶ This variation in response is usually assumed to be due to a difference in chamber volume, but it could also be due to a difference in the perturbation factors. For example, a slight change in the front or rear wall thicknesses of the NACP-02 chamber could significantly change P_{wall} . This is something that MC simulations cannot predict if the exact construction data are not available for each individual chamber. In this context, PSDs could be used to experimentally extract perturbation factors for a specific ion chamber.

As we have noted, in this work, no attempt was made to extract absolute perturbation factors. In theory, this could be done if the PSD was calibrated against an absolute reference such as a water calorimeter. This will be the subject of a future work.

Figures 6–11 indicate that there is a reduction in the relative perturbation factors if the front window is scaled and the EPOM is placed inside the air cavity, which suggests that it might be possible that a suitable choice of EPOM could eliminate the need for perturbation factors.

TABLE I. Physical and water-equivalent scaling for the NACP-02 and Roos chambers.

NACP-02 chamber		Window	Front electrode
Material		Mylar™	Graphite
Physical thickness (mm)	t_m	0.1	0.5
Density (g/cm ³)	ρ_m	1.4	2.25
Stopping power relative to water	$S_{m,w}$	0.92	0.88
Water-equivalent thickness	$t_m, \rho_m, S_{m,w}$	0.13	0.99
Total water-equivalent front wall thickness		1.12 mm	
Roos chamber		Window	Front electrode
Material		0.1 mm varnish+1 mm PMMA	Graphite dag
Physical thickness (mm)	t_m	1.1	0.02
Density (g/cm ³)	ρ_m	1.18	0.82
Stopping power relative to water	$S_{m,w}$	0.96	0.88
Water-equivalent thickness	$t_m, \rho_m, S_{m,w}$	1.24	0.01
Total water-equivalent front wall thickness		1.26 mm	

IV.A. EPOM

Section III C provided the relative perturbation factors as a function of depth for two EPOMs: 0.6 and 1.0 mm for the NACP-02 chamber and 1.0 and 1.15 mm for the Roos chamber. It can be seen on Figs. 7–9 and Figs. 10 and 11 that using a 0.6 mm EPOM for the NACP-02 chamber and a 1.0 mm EPOM for the Roos chamber (the physical window thickness) provide relative perturbation factors that increase substantially with depth at all energies. In contrast, using a 1.0 mm EPOM for the NACP-02 chamber and a 1.15 mm EPOM for the Roos chamber (the water-equivalent thicknesses) decreases the variation in relative perturbation factors with depth, especially for 6 MeV. The following question could therefore be asked: What is the optimal EPOM to use for each ion chamber?

Table I presents what we believe are the most up-to-date construction characteristics for the NACP-02 and the Roos chambers. According to these data, the water-equivalent depth is 1.12 mm for the NACP-02 chamber and 1.26 mm for the Roos chamber; therefore, the water-equivalent EPOM is located away from the inside front face and closer to the center of the chamber air cavity in both cases. Both of these EPOM values are higher than those used in this work but the change is coincidentally in the same direction, which explains the good agreement seen between the two chamber types in Fig. 5.

Is this water-equivalent EPOM the optimal EPOM to use to eliminate the variation of the relative perturbation factors

with depth? The optimal EPOM can be found by adjusting the shift between the PSD and ion chamber depth-dose curves to minimize the variation in the resulting relative perturbation factors with depth. Table II shows the results of this exercise.

The positioning tolerances indicated in Table II are estimated from the tolerances on the relative perturbation factors.

Table II shows that one single EPOM for all energies does not provide the optimal performance, which is not unexpected following the earlier discussion of chamber perturbation factors and EPOM. There is a clear trend toward a higher EPOM with energy. Furthermore, using an EPOM at the water-equivalent depth (1.12 mm for the NACP-02 chamber and 1.26 mm for the Roos chamber) is not sufficient to match the PSD depth-dose curve at 12 and 18 MeV. This energy dependence is consistent with the findings of Wang and Rogers,¹⁹ who calculated a 0.55–0.65 mm shift from the inner face of the front wall (depending on the front window thickness assumed) for the NACP-02 chamber in a 6 MeV electron beam and a 0.7–0.8 mm shift in a 22 MeV electron beam. Our results indicate a 0.4 mm shift from the inner face of the front wall at 6 MeV and a 1.2 mm shift at 18 MeV for the NACP-02 chamber. Given the uncertainties, this agreement is very good.

Zink and Wulff²⁰ calculated the optimal EPOM for a Roos chamber in electron beams and concluded that a 0.4 mm shift will provide an energy independent minimization of the per-

TABLE II. Optimal EPOM for the NACP-02 and Roos chambers for 6, 12, and 18 MeV.

Chamber	EPOM(mm) $\pm$ 0.1 mm	EPOM(mm) $\pm$ 0.1 mm	EPOM(mm) $\pm$ 0.2 mm
	6 MeV	12 MeV	18 MeV
NACP-02	1.0	1.25	1.8
Roos	1.12	1.4	1.9

turbation factors. Their EPOM was placed at 0.4 mm below the surface of the front window. Zink and Wulff optimized the EPOM only up to about R_{50} , while we have optimized the EPOM up to R_p . Reanalyzing our data to optimize the EPOM to R_{50} , we find a slight increase in EPOM toward the center of the air cavity for all energies; however, no single EPOM will provide a quasienergy independent EPOM for the Roos chamber, which is contradictory to the findings of Zink and Wulff. However, it is true that placing the EPOM 0.4 mm inside the air cavity from the front wall is a reasonable “best choice” for all electron energies studied here.

V. CONCLUSION

This work presents the experimental extraction of relative perturbation factors in megavoltage electron beams for NACP-02 and Roos parallel-plate chambers using a PSD. Both the NACP-02 and the Roos chambers are not perturbation-free, contrary to what has long been assumed. Coincidentally, both the NACP-02 and the Roos chambers provide depth doses that are identical to the 0.1–0.15 mm level. This is one of the reasons why these chambers were long assumed to be perturbation-free. These perturbations indicate that when using an NACP-02 chamber with the 0.6 mm EPOM as suggested by the TG-51 protocol, the differences between the true and the measured R_{50} are 0.4, 1.0, and 1.2 mm at 6, 12, and 18 MeV, respectively. The existence of perturbation factors has implications for reference dosimetry (e.g., $k'_{R_{50}}$ in TG-51 needs to be modified to take into account chamber perturbations).

Placing the EPOM at the inside face of the front window is not optimal. The use of an EPOM placed inside the air cavity for parallel-plate chambers removes much of the variation of the relative perturbation factor with depth; however, the optimal EPOM appears to be energy dependent and different from the water-equivalent front window thickness.

This work has demonstrated that depth-dose curves can be measured in electron beams using a PSD with a precision high enough to allow the extraction of the perturbation factors for parallel-plate chambers. This illustrates the fact that PSD technology is maturing rapidly and that PSDs now constitute a credible alternative to other water-equivalent detectors, such as liquid ion chambers, diamond detectors, and radiochromic film. This work also provides experimental confirmation that the Monte Carlo calculations of perturbation factors presented in the literature are correct at the 0.7% level.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) Discovery Grant No. 357402, and in part by NSERC Discovery Grant No. 262105 and the National Cancer Institute (NCI) (Grant No. CA120198-01A2). Mathieu Guillot acknowledges the NSERC for financial support through a postgraduate scholarship.

^{a)} Author to whom correspondence should be addressed. Electronic mail: frederic.lacroix.chum@ssss.gouv.qc.ca

¹ P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. S. Huq, R. Nath, and D. W. Rogers, “AAPM’s TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams,” *Med. Phys.* **26**, 1847–1870 (1999).

² F. Tessier and I. Kawrakow, “Effective point of measurement of thimble ion chambers in megavoltage photon beams,” *Med. Phys.* **37**, 96–107 (2010).

³ P. Andreo, D. T. Burns, K. Hohlfeld, M. S. Huq, T. Kanai, F. Laitano, V. G. Smyth, and S. Vynckier, “Absorbed dose determination in external beam radiotherapy: An international code of practice for dosimetry based on standards of absorbed dose to water,” IAEA Technical Reports Series No. 398 (International Atomic Energy Agency, Vienna, 2000).

⁴ NAR, “Procedures of dosimetry with probe-type detectors for photon and electron radiation: Part 2. Ionization chamber dosimetry of high energy photon and electron radiation,” NAR Technical Report No. DIN6800–2 (Normenausschuß Radiologie im DIN, 2008).

⁵ D. I. Thwaites, A. R. DuSautoy, T. Jordan, M. R. McEwen, A. Nisbet, A. E. Nahum, and W. G. Pitchford, “The IPEM code of practice for electron dosimetry for radiotherapy beams of initial energy from 4 to 25 MeV based on an absorbed dose to water calibration,” *Phys. Med. Biol.* **48**, 2929–2970 (2003).

⁶ C. S. Reft and F. T. Kuchnir, “Measured overall perturbation factors at depths greater than $d_{\max}$ for ionization chambers in electron beams,” *Med. Phys.* **26**, 208–213 (1999).

⁷ H. Casson and J. P. Kiley, “Replacement correction factors for electron measurements with a parallel-plate chamber,” *Med. Phys.* **14**, 216–217 (1987).

⁸ C. Cinos, M. Lizuain, and M. Febrian, “Total perturbation correction factor for PTW and NACP plane parallel chambers in electron beams,” *Radiother. Oncol.* **21**, 135–140 (1991).

⁹ C. S. Reft and F. T. Kuchnir, “Experimental determination of the overall perturbation factor for the NACP chamber in electron beams for $d_{\max} < d < \text{or} = d_{80}$,” *Phys. Med. Biol.* **46**, N49–N55 (2001).

¹⁰ M. A. Hunt, G. J. Kutcher, and A. Buffa, “Electron backscatter corrections for parallel-plate chambers,” *Med. Phys.* **15**, 96–103 (1988).

¹¹ S. C. Klevenhagen, “Implication of electron backscattering for electron dosimetry,” *Phys. Med. Biol.* **36**, 1013–1018 (1991).

¹² M. McEwen, H. Palmans, and A. Williams, “An empirical method for the determination of wall perturbation factors for parallel-plate chambers in high-energy electron beams,” *Phys. Med. Biol.* **51**, 5167–5181 (2006).

¹³ F. Verhaegen, “Interface perturbation effects in high-energy electron beams,” *Phys. Med. Biol.* **48**, 687–705 (2003).

¹⁴ J. Sempau, P. Andreo, J. Aldana, J. Mazurier, and F. Salvat, “Electron beam quality correction factors for plane-parallel ionization chambers: Monte Carlo calculations using the PENELOPE system,” *Phys. Med. Biol.* **49**, 4427–4444 (2004).

¹⁵ F. Verhaegen, R. Zakikhani, A. DuSautoy, H. Palmans, G. Bostock, D. Shipley, and J. Seuntjens, “Perturbation correction factors for the NACP-02 plane-parallel ionization chamber in water in high-energy electron beams,” *Phys. Med. Biol.* **51**, 1221–1235 (2006).

¹⁶ L. A. Buckley and D. W. O. Rogers, “Wall correction factors, P_{wall} for parallel-plate ionization chambers,” *Med. Phys.* **33**, 1788–1796 (2006).

¹⁷ F. Araki, “Monte Carlo calculations of correction factors for plane-parallel ionization chambers in clinical electron dosimetry,” *Med. Phys.* **35**, 4033–4040 (2008).

¹⁸ E. Chin, H. Palmans, D. Shipley, M. Bailey, and F. Verhaegen, “Analysis of dose perturbation factors of a NACP-02 ionization chamber in clinical electron beams,” *Phys. Med. Biol.* **54**, 307–326 (2009).

¹⁹ L. L. W. Wang and D. W. O. Rogers, “Study of the effective point of measurement for ion chambers in electron beams by Monte Carlo simulation,” *Med. Phys.* **36**, 2034–2042 (2009).

²⁰ K. Zink and J. Wulff, “Positioning of a plane-parallel ionization chamber in clinical electron beams and the impact on perturbation factors,” *Phys. Med. Biol.* **54**, 2421–2435 (2009).

²¹ G. Bruggmoser, R. Saum, and F. Schmid, “Wo befindet sich der effektive Messort einer PTW 34001 Roos Kammer,” in *Dreilaendertagung fuer Medizinische Physik*, edited by R. Mini (HRG, Bern, 2007).

²² M. R. McEwen and A. R. DuSautoy, “Primary standards of absorbed dose for electron beams,” *Metrologia* **46**, S59–S79 (2009).

²³ C. Richter, J. Pawelke, L. Karsch, and J. Woihte, “Energy dependence of EBT-1 radiochromic film response for photon (10 kVp–15 MVp) and

- electron beams (6–18 MeV) readout by a flatbed scanner,” *Med. Phys.* **36**, 5506–5514 (2009).
- ²⁴S.-T. Chiu-Tsao, Y. Ho, R. Shankar, L. Wang, and L. B. Harrison, “Energy dependence of response of new high sensitivity radiochromic films for megavoltage and kilovoltage radiation energies,” *Med. Phys.* **32**, 3350–3354 (2005).
- ²⁵A. Rink, I. A. Vitkin, and D. A. Jaffray, “Energy dependence (75 kVp to 18 MV) of radiochromic films assessed using a real-time optical dosimeter,” *Med. Phys.* **34**, 458–463 (2007).
- ²⁶H. Bouchard, F. Lacroix, G. Beaudoin, J.-F. Carrier, and I. Kawrakow, “On the characterization and uncertainty analysis of radiochromic film dosimetry,” *Med. Phys.* **36**, 1931–1946 (2009).
- ²⁷I. Griessbach, M. Lapp, J. Bohsung, G. Gademann, and D. Harder, “Dosimetric characteristics of a new unshielded silicon diode and its application in clinical photon and electron beams,” *Med. Phys.* **32**, 3750–3754 (2005).
- ²⁸M. McEwen and C. Ross, “Unexpected doserate dependencies of diodes for beam scanning,” *Med. Phys.* **35**, 2920–2920 (2008).
- ²⁹A.-M. Frelin, J.-M. Fontbonne, G. Ban, J. Colin, M. Labalme, A. Batalla, A. Isambert, A. Vela, and T. Leroux, “Spectral discrimination of Cerenkov radiation in scintillating dosimeters,” *Med. Phys.* **32**, 3000–3006 (2005).
- ³⁰F. Lacroix, L. Archambault, L. Gingras, M. Guillot, A. S. Beddar, and L. Beaulieu, “Clinical prototype of a plastic water-equivalent scintillating fiber dosimeter array for QA applications,” *Med. Phys.* **35**, 3682–3690 (2008).
- ³¹F. Pönisch, L. Archambault, T. M. Briere, N. Sahoo, R. Mohan, S. Beddar, and M. T. Gillin, “Liquid scintillator for 2D dosimetry for high-energy photon beams,” *Med. Phys.* **36**, 1478–1485 (2009).
- ³²A.-M. Frelin, J.-M. Fontbonne, G. Ban, J. Colin, M. Labalme, A. Batalla, A. Vela, P. Boher, M. Braud, and T. Leroux, “The DosiMap, a new 2D scintillating dosimeter for IMRT quality assurance: Characterization of two Cerenkov discrimination methods,” *Med. Phys.* **35**, 1651–1662 (2008).
- ³³L. Archambault, J. C. Polf, L. Beaulieu, and S. Beddar, “Characterizing the response of miniature scintillation detectors when irradiated with proton beams,” *Phys. Med. Biol.* **53**, 1865–1876 (2008).
- ³⁴A. S. Beddar, T. R. Mackie, and F. H. Attix, “Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical consideration,” *Phys. Med. Biol.* **37**, 1883–1900 (1992).
- ³⁵A. S. Beddar, T. R. Mackie, and F. H. Attix, “Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements,” *Phys. Med. Biol.* **37**, 1901–1913 (1992).
- ³⁶“Clinical dosimetry measurements in radiotherapy,” *Medical Physics Monograph No. 34*, edited by D. W. O. Rogers and J. E. Cygler (AAPM, New York, 2009).
- ³⁷A. S. Beddar, T. M. Briere, F. A. Mourtada, O. N. Vassiliev, H. H. Liu, and R. Mohan, “Monte Carlo calculations of the absorbed dose and energy dependence of plastic scintillators,” *Med. Phys.* **32**, 1265–1269 (2005).
- ³⁸Task Group 21, Radiation Therapy Committee of the AAPM, “A protocol for the determination of absorbed dose from high-energy photon and electron beams,” *Med. Phys.* **10**, 741–771 (1983).
- ³⁹D. T. Burns, G. X. Ding, and D. W. O. Rogers, “ R_{50} as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry,” *Med. Phys.* **23**, 383–388 (1996).
- ⁴⁰C. K. Ross, M. R. McEwen, A. F. McDonald, C. D. Cojocaru, and B. A. Faddegon, “Measurement of multiple scattering of 13 and 20 MeV electrons by thin foils,” *Med. Phys.* **35**, 4121–4131 (2008).
- ⁴¹M. R. McEwen, I. Kawrakow, and C. K. Ross, “The effective point of measurement of ionization chambers and the build-up anomaly in MV x-ray beams,” *Med. Phys.* **35**, 950–958 (2008).
- ⁴²E. Chin, D. Shipley, M. Bailey, J. Seuntjens, H. Palmans, A. DuSautoy, and F. Verhaegen, “Validation of a Monte Carlo model of a NACP-02 plane-parallel ionization chamber model using electron backscatter experiments,” *Phys. Med. Biol.* **53**, N119–N126 (2008).
- ⁴³F. Lacroix, A. S. Beddar, M. Guillot, L. Beaulieu, and L. Gingras, “A design methodology using signal-to-noise ratio for plastic scintillation detectors design and performance optimization,” *Med. Phys.* **36**, 5214–5220 (2009).
- ⁴⁴F. Lacroix, L. Beaulieu, L. Archambault, and A. S. Beddar, “Simulation of the precision limits of plastic scintillation detectors using optimal component selection,” *Med. Phys.* **37**, 412–418 (2010).
- ⁴⁵J. Lambert, Y. Yin, D. R. McKenzie, S. Law, and N. Suchowerska, “Cerenkov-free scintillation dosimetry in external beam radiotherapy with an air core light guide,” *Phys. Med. Biol.* **53**, 3071–3080 (2008).
- ⁴⁶J. Lambert, Y. Yin, D. R. McKenzie, S. H. Law, A. Ralston, and N. Suchowerska, “A prototype scintillation dosimeter customized for small and dynamic megavoltage radiation fields,” *Phys. Med. Biol.* **55**, 1115–1126 (2010).
- ⁴⁷B. A. Faddegon, D. Sawkey, T. O’Shea, M. McEwen, and C. Ross, “Treatment head disassembly to improve the accuracy of large electron field simulation,” *Med. Phys.* **36**, 4577–4591 (2009).
- ⁴⁸M. R. McEwen, A. J. Williams, and A. R. DuSautoy, “Trial calibrations of therapy level electron beam ionisation chambers in terms of absorbed dose to water,” NPL Report No. CIRM 20 (National Physical Laboratory, Teddington, United Kingdom, 1998). Available at www.npl.co.uk.