Calculation of water and graphite perturbation correction factors for
the NACP-02 plane-parallel ionization chamber in high-energy
electron beams

A thesis submitted to McGill University in partial fulfillment of the requirements of
the degree of Master of Science in Medical Radiation Physics

by

Erika Chin
Medical Physics Unit (MUHC)
McGill University, Montreal
Quebec, Canada

August 2007
Abstract

For megavoltage electron beams, current dosimetry protocols assume well-guarded plane-parallel ionization chambers have electron perturbation correction factors of unity. Papers by other researchers have shown the contrary. The National Physical Laboratory (NPL), Teddington UK, has an electron calibration service that requires knowledge of perturbation factors in water over graphite, $p_{ref,w}/p_{ref,g}$, for their NACP-02 chamber. Using the Monte Carlo code EGSnrcMP, perturbation correction factors at $z_{ref}$ in graphite for the NPL’s Radiation Dynamics linac 4 – 19 MeV were calculated. These results combined with those in water calculated by Zakikhani (2006) showed that only the $p_{ref,w}/p_{ref,g}$ of the 4 MeV and 12 MeV beams, at $1.0080 \pm 0.027 \%$ and $1.0071 \pm 0.028 \%$, were significantly different from unity.

Perturbation correction factors in water and graphite for the Varian clinical linacs 4 – 18 MeV were also investigated. Important issues that arose requiring further study included the discrepancy in results caused by 1 keV vs. 10 keV transport cutoffs and whether the depth of the effective point of measurement should account for the phantom equivalent thickness of the chamber window.
Résumé

Pour les faisceaux d’électrons de haute énergie (MV), les protocoles de dosimétrie actuels supposent que les chambres d’ionisation à plaques parallèles ont des facteurs de correction de perturbation électronique égaux à l’unité. Plusieurs articles d’autres auteurs ont démontré le contraire. Le National Physical Laboratory (NPL), Teddington Royaume-Uni, possède un service d’étalonnage qui requiert de savoir les facteurs de perturbation de l’eau par rapport au graphite, $p_{ref,w}/p_{ref,g}$, pour leur chambre NACP-02. A l’aide du code Monte Carlo EGSnrcMP, les facteurs de correction de perturbation à $z_{ref}$ dans le graphite ont été calculés pour le linac Radiation Dynamics du NPL à des énergies de 4-19 MeV. Ces résultats, combinés à ceux dans l’eau calculés par Zakikhani (2006), ont montré que seulement les $p_{ref,w}/p_{ref,g}$ des faisceaux de 4 MeV et 12 MeV, à $1,0080 \pm 0,27 \%$ et $1,0071 \pm 0,28 \%$ respectivement, étaient significativement différents de l’unité.

Les facteurs de correction de perturbation dans l’eau et dans le graphite ont aussi été étudiés pour les linacs cliniques de Varian à 4-18 MeV. D’importants problèmes ont alors été soulevés, notamment des différences dans les résultats causés par des énergies de coupure de 1 keV par rapport à 10 keV ainsi que la question de savoir si la profondeur du point de mesure devrait prendre en compte l’épaisseur effective de la fenêtre d’entrée. Ces problèmes requièrent davantage d’études.
Acknowledgements

This work was completed with the help of many people. I would first like to thank my supervisors Dr. Frank Verhaegen and Dr. Jan Seuntjens for their central role in guiding and supporting me throughout this work. Their knowledge and experience were invaluable. Key advice and direction were also provided during monthly progress meetings with the great physicists from the National Physical Laboratory (NPL) in the UK, namely David Shipley, Hugo Palmans, Mark Bailey and Alan DuSautoy. I would particularly like to thank David Shipley and Hugo Palmans for setting up and running my computer simulations on the NPL computer grid. This project also would not have been completed in a timely manner if not for the tremendous efforts of Dr. Wamied Abdel-Rahman to keep the McGill computer cluster up and running. Robin Van Gils was a great help in constructing and providing all the materials and phantoms required for my backscatter experiments. Dr. Podgorsak also deserves a great deal of recognition for building a highly regarded medical physics department full of wonderful people. It was a pleasure to work in this environment. Finally, I would not be where I am today without all my family and friends.

This work was funded by the National Physical Laboratory (UK).
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Title Page</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Abstract</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Acknowledgements</strong></td>
<td>4</td>
</tr>
<tr>
<td><strong>Table of Contents</strong></td>
<td>5</td>
</tr>
<tr>
<td><strong>Chapter 1  Introduction</strong></td>
<td>7</td>
</tr>
<tr>
<td>1.1 Electron perturbation correction factors in water</td>
<td>7</td>
</tr>
<tr>
<td>1.2 Electron perturbation correction factors in graphite</td>
<td>10</td>
</tr>
<tr>
<td>1.3 Stopping power ratios</td>
<td>11</td>
</tr>
<tr>
<td>1.4 The Monte Carlo method</td>
<td>12</td>
</tr>
<tr>
<td>1.5 The EGSnrcMP Monte Carlo code</td>
<td>13</td>
</tr>
<tr>
<td>1.6 Motivation of this thesis work</td>
<td>14</td>
</tr>
<tr>
<td>1.7 Scope of this thesis work</td>
<td>15</td>
</tr>
<tr>
<td><strong>Chapter 2  Literature Review</strong></td>
<td>17</td>
</tr>
<tr>
<td>2.1 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber in water</td>
<td>17</td>
</tr>
<tr>
<td>2.2 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber in graphite</td>
<td>21</td>
</tr>
<tr>
<td><strong>Chapter 3  Materials and Methods</strong></td>
<td>23</td>
</tr>
<tr>
<td>3.1 Validation of the CL21EX and CL2300C/D Varian linac BEAMnrcMP Monte Carlo models</td>
<td>23</td>
</tr>
<tr>
<td>3.2 Validation of the NACP-02 chamber BEAMnrcMP Monte Carlo model</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Calculation of stopping power ratios</td>
<td>31</td>
</tr>
<tr>
<td>3.4 Calculation of water and graphite electron perturbation correction factors for the NACP-02 plane-parallel chamber at depths between $z_{ref}$ and $R_{50}$</td>
<td>31</td>
</tr>
<tr>
<td>3.5 Other investigations in water and graphite electron perturbation correction factors for the NACP-02 plane-parallel chamber</td>
<td>34</td>
</tr>
</tbody>
</table>
# Table of Contents

## Chapter 4  Results

4.1 Validation of the CL21EX and CL2300C/D Varian linac BEAMnrcMP Monte Carlo models

4.2 Validation of the Monte Carlo model for NACP-02 plane parallel ionization chamber with backscatter factors

4.3 Mean Spencer-Attix mass restricted collisional stopping power ratios

4.4 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber

4.4.1 Perturbation factor results calculated in water

4.4.2 Perturbation factor results calculated in graphite

4.4.3 Perturbation factor ratios in the NPL calibration process

4.4.4 Scaling the NACP-02 front chamber window for the phantom material’s equivalent thickness

4.4.5 Hypothesis explaining the decrease in $p_{wall}$ value with depth in a water phantom

4.4.6 The effects of the NACP-02’s side, back, and front chamber walls on the value of $p_{wall}$ in water and graphite phantoms

4.4.7 Hypothesis explaining the increase in $p_{cav}$ value with depth in water and graphite phantoms

## Chapter 5  Conclusion

## References
Chapter 1 Introduction

One of the main modalities used in cancer treatment is radiation therapy, also known as radiotherapy. The majority of radiotherapy applications use high energy photons or electrons to kill cancer cells directly or indirectly by interfering with their reproduction. Accurate delivery of the radiation absorbed dose to the tumour target is critical in ensuring the success of the radiation treatment. A dose too low will fail to eradicate the tumour but a dose too high could potentially lead to severe or fatal normal tissue complications. Report 24 by the International Commission on Radiation Units and Measurements (ICRU) recommends an uncertainty of 5% in the accuracy of dose delivery to achieve an acceptable Tumour Control Probability (TCP). It is therefore important to reduce the uncertainties in each step of the dosimetry chain as all uncertainties are usually added in quadrature to estimate the overall uncertainty.

One of the main steps in the dosimetry chain is the conversion of measured ionized charge produced in a medium due to exposure from a radiation beam, to the absorbed dose-to-medium. Charge is typically measured using an ionization chamber. However, when an ionization chamber is inserted into the path of the radiation beam, the presence of the chamber will perturb the fluence of the particles that we are attempting to measure. Perturbation correction factors are thus required to correct for the disturbance caused by the ionization chamber. The work of this thesis focuses specifically on perturbation correction factors in water and graphite phantoms for the NACP-02 plane-parallel ionization chamber (IBA-Scanditronix, Uppsala, Sweden) in high energy electron beams.

1.1 Electron perturbation correction factors in water

Water is used as the nearest tissue equivalent material and hence most standards laboratories and clinical radiotherapy centres perform their calibrations and
measurements in water phantoms. Perturbation correction factors for electron beams in water phantoms are therefore of great interest.

There are several dosimetry protocols for clinical high-energy electron beams (3-50 MeV) such as the AAPM TG-51 (1999), the IAEA TRS-398 (2000), and the IPEM (2003). This section will use the methodology of the IAEA TRS-398. Absorbed dose-to-water at the reference depth, $z_{ref}$, is then given by

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0},$$

(1.1)

where $M_Q$ is the reading of the ionization chamber corrected for temperature, pressure, polarity, and ion recombination. $N_{D,w,Q_0}$ is the absorbed dose-to-water calibration factor of the ionization chamber for the calibration beam quality $Q_0$, and $k_{Q,Q_0}$ is the beam quality conversion factor that accounts for the difference in chamber response between the calibration beam quality, $Q_0$, and the user’s beam quality, $Q$. The reference depth in water, $z_{ref}$, for an electron beam is defined as

$$z_{ref} = 0.6R_{50} - 0.1 \text{ (cm)}$$

(1.2)

where $R_{50}$ is the depth at which the percent depth dose (PDD) curve in water is at 50%. $R_{50}$ is used as the beam quality specifier.

The beam quality conversion factor, $k_{Q,Q_0}$, can be calculated based on Bragg-Gray cavity theory as the ratio of mean Spencer-Attix mass restricted collisional stopping-power ratio water to air ($s_{w,air}$) for the user’s beam quality, $Q$, over that of the calibration beam quality, $Q_0$. However, Bragg-Gray cavity theory has two conditions. The first is that the cavity of our ionization chamber does not perturb the fluence of the charged particles in the surrounding medium. The second condition is that no charged particles are produced in the cavity by the primary beam and that all
dose deposited in the cavity comes only from charged particles crossing the cavity. Ionization chambers usually do not meet these two conditions and hence the formula for \( k_{Q,Q_b} \) also requires perturbation correction factors denoted by \( p_Q \) and \( p_{Q_b} \) for the user’s beam and the calibration beam respectively. The beam quality conversion factor is therefore specified by

\[
k_{Q,Q_b} = \frac{(s_{w,air})_Q P_Q}{(s_{w,air})_{Q_b} P_{Q_b}}. \tag{1.3}
\]

The perturbation factor \( p_Q \) can be factorized into 4 components,

\[
p_Q = p_{cav} p_{wall} p_{dis} p_{cel}. \tag{1.4}
\]

\( p_{cav} \) corrects for the fluence perturbation due to in-scattering and obliquity when the medium in the scoring volume is replaced by an air cavity. \( p_{wall} \) corrects for the fluence perturbation caused by the non-medium equivalence of the chamber wall materials. Finally, \( p_{dis} \) corrects for the fact that the charged particle fluence in the air cavity is actually representative of the fluence somewhere upstream in the higher density medium and \( p_{cel} \) corrects for the effects of the central electrode on the chamber response (Andreo et al 2000). For the well guarded plane-parallel ionization chambers such as the NACP-02, \( p_{dis} \) and \( p_{cel} \) are not required as the depth of the effective point of measurement is taken to be the inside centre of the front chamber window and plane-parallel chambers do not have central electrodes. The formula for \( p_Q \) thus reduces to

\[
p_Q = p_{cav} p_{wall}. \tag{1.5}
\]
Chapter 1

1.2 Electron perturbation correction factors in graphite

The National Physical Laboratory (NPL) in Teddington, UK calibrates plane-
parallel ionization chambers in terms of absorbed dose to water in electron beams
based on a primary standard graphite calorimeter. The calibration process involves a
conversion from dose to graphite to dose to water, which requires knowledge of
perturbation factors for the NACP-02 plane-parallel ionization chamber in both
media. The mean density of the NPL’s graphite phantom is 1.77 g/cm³. The process
was described by McEwen et al (1998). The reference depth for a given electron
beam energy in the graphite phantom at which measurements are made, \( d_g \), is defined
as

\[
d_g = d_w \frac{R_{50,g}}{R_{50,w}} \text{ (cm)}
\]  

(1.6)

where \( d_w \) is the reference depth in water. \( d_w \) can also be denoted by \( z_{\text{ref}} \) and was
defined in equation 1.2. \( R_{50,g} \) and \( R_{50,w} \) are the respective depths in graphite and water
where the PDD value is 50%. The reference NACP-02 plane-parallel chamber of the
NPL is calibrated at depth \( d_g \) against the graphite calorimeter to obtain the reference
chamber’s absorbed dose-to-graphite calibration coefficient, \( N_{D,\text{ref},g} \).

\[
N_{D,\text{ref},g} = \frac{D_g}{M_{\text{ref},g}}
\]  

(1.7)

\( D_g \) is the dose obtained from the calorimeter and \( M_{\text{ref},g} \) is the corrected reference
chamber reading in graphite. From Bragg-Gray cavity theory, a theoretical
conversion can be performed to find the NACP-02 reference chamber’s absorbed
dose-to-water calibration coefficient, \( N_{D,\text{ref},w} \).

\[
N_{D,\text{ref},w} = N_{D,\text{ref},g} \frac{P_{\text{ref},w} s_{w,\text{air}}}{P_{\text{ref},g} s_{g,\text{air}}}
\]  

(1.8)
As ionization chambers do not have an ideal Bragg-Gray cavity, perturbation correction factors in both water and graphite are required. \( p_{\text{ref},w} \) and \( p_{\text{ref},g} \) are the respective perturbation factor, \( p_Q \), for the NPL’s NACP-02 reference chamber in water and graphite phantoms. \( s_{w,\text{air}} \) and \( s_{g,\text{air}} \) are the respective water-to-air and graphite-to-air mean Spencer-Attix mass restricted collisional stopping-power ratios. Finally, the user chamber’s absorbed dose-to-water calibration coefficient, \( N_{D,\text{user},w} \), can be derived by direct comparison to the NPL’s NACP-02 reference chamber at reference depth, \( d_w \), in water in the NPL beam.

\[
N_{D,\text{user},w} = N_{D,\text{ref},w} \frac{M_{\text{ref},w}}{M_{\text{user},w}} \quad (1.9)
\]

\( M_{\text{ref},w} \) and \( M_{\text{user},w} \) are the respective corrected readings in water for the NPL’s NACP-02 reference chamber and the user’s chamber.

1.3 Stopping power ratios

Calculations in sections 1.1 and 1.2 require the Spencer-Attix stopping power ratios water-to-air and graphite-to-air. It will also be shown in section 3.4 that Spencer-Attix stopping power ratios are required for electron perturbation correction factor calculations. For calculating stopping power ratios water-to-air, \( s_{w,\text{air}} \), both the AAPM’s TG-51 protocol for reference beam dosimetry and the IAEA’s TRS-398 Code of Practice recommend using the equations of Burns et al (1996). These equations were derived from \( s_{w,\text{air}} \) data obtained from realistic Monte Carlo simulations of 24 clinical beams. At depth \( z_{\text{ref}} \), water-to-air stopping power ratio is given as

\[
s_{w,\text{air}}(R_{50}, z_{\text{ref}}) = 1.2534 - 0.1487(R_{50})^{0.2144}, \quad (1.10)
\]

and for all other depths \( z \), it is
The Monte Carlo method

All calculations and simulations in this thesis will use the EGSnrcMP Monte Carlo code (Kawrakow et al 2006(b)). The Monte Carlo method refers to a class of computational algorithms that simulate physical or mathematical systems in a non-deterministic manner through the use of random numbers. It is used to find solutions to problems whose large number of variables and complexity make it impossible or impractical to solve using analytical methods. Originally used in the 1930’s and 1940’s to investigate photon and neutron transport for nuclear power applications, its application has spread to many other areas including radiotherapy physics (Verhaegen and Seuntjens 2003).
The Monte Carlo method is a powerful tool for studying transport of particles such as photons and electrons in radiotherapy physics due to the complex geometries of patients and radiation sources and the wide range of atomic numbers and densities in the materials involved. Random trajectories of individual particles are simulated by “using machine-generated (pseudo)-random numbers to sample from the probability distributions governing the physical processes” (Rogers and Bielajew 1990). By tracking a large number of particles and their changing properties, quantities of interest such as absorbed dose distribution, energy spectral distribution, and angular distribution at given regions in a medium can be found. Not only can Monte Carlo simulations of problems be a simple complementary technique next to experimental measurements, but in many cases it is the only option. For example, finding what fraction of the dose to a particular region in the medium came from particles travelling through the front, side, or back of the scoring volume. Or for the work in this thesis, it would be extremely difficult to perform an experiment that could separate the fluence perturbation caused by the chamber’s walls, $p_{\text{wall}}$, from the fluence perturbation caused by the chamber’s air cavity, $p_{\text{cav}}$.

1.5 The EGSnrcMP Monte Carlo code

There are many available Monte Carlo codes for modelling radiotherapy beams: ETRAN (Seltzer 1991), EGS4 (Nelson et al 1985), EGSnrc (Kawrakow 2000), PENEOPE (Sempau et al 1997), MCNP5 (RSICC 2003), and GEANT4 (2003). All are written in FORTRAN programming language except GEANT4, which was written with C++ (Verhaegen and Seuntjens 2003). For this work, we are using EGSnrcMP Monte Carlo code which is maintained by the Ionizing Radiation Standards Group, Institute for National Measurement Standards at the National Research Council of Canada, Ottawa.

The EGSnrcMP is an updated multi-platform environment for running the EGSnrc Monte Carlo code. It is capable of running on Linux/Unix, Windows
NT/2000/XP, and Mac OSX, whereas EGSnrc only worked for a selection of Linux/Unix systems (Kawrakow et al 2006(b)). The EGSnrcMP/EGSnrc code is based on the EGS4 (electron-gamma-shower) code system for coupled transport of electrons and photons that was developed at the Stanford Linear Accelerator Centre (SLAC). A major flaw in EGS4 was the strong dependence of calculated results on electron step-size. This and other shortcomings have been corrected for in EGSnrcMP/EGSnrc with a new multiple elastic scattering theory, an improved electron-step algorithm, an exact boundary crossing algorithm, new elastic electron scattering cross-sections (involving relativistic and spin effects), and more accurate evaluation of energy loss in sub-threshold processes (Kawrakow 2000, Rogers et al 2001).

EGSnrcMP/EGSnrc has been extensively benchmarked for realistic ionization chamber and various photon and electron energies (Seuntjens et al 1999, Borg et al 2000, Verhaegen 2003). As well, its user interface allows for easy modeling of radiotherapy linacs, chambers, and phantoms making it a highly suitable tool for radiotherapy investigations.

1.6 Motivation of this thesis work

For all well guarded plane-parallel ionization chambers in megavoltage electron beams, recent international protocols (e.g. AAPM’s TG-51, IAEA’s TRS-398) assume a value of unity for perturbation correction factors used in the calculation of $k_{Q,Q_b}$ values in a water phantom. However, data published by various groups have indicated the contrary (see Chapter 2: Literature Review). Well guarded plane-parallel ionization chambers refer to chambers whose guard ring widths have been optimized to eliminate the effect of in-scattering (Roos et al 1993). This work will focus on using EGSnrcMP Monte Carlo (MC) simulations to calculate electron perturbation correction factors in water phantoms and graphite phantoms for the
1.7 Scope of this thesis work

Scanditronix NACP-02 plane-parallel ionization chamber. Water is commonly used in both standard laboratories and in radiotherapy cancer clinics for chamber calibrations. Graphite is used by the National Physical Laboratory in the UK for their chamber calibration service. Dosimetry protocols recommend using either the NACP-02 or the PTW Roos plane-parallel ionization chamber for megavoltage electron beams.

Electron perturbation correction factors in water have already been investigated by Verhaegen et al (2006) and Buckley and Rogers (2006). There are two reasons why some of the previously published data is recalculated in this thesis. The first is to determine whether tuning the Monte Carlo (MC) NACP-02 chamber model against backscatter measurements will have a significant impact on the calculated correction factors. In the work by Verhaegen et al (2006), some tuning of the chamber model was attempted with limited success. Buckley and Rogers (2006) attempted no tuning of the chamber model. Secondly, the factors were recalculated so that further analysis could be performed to explain why the perturbation correction factors increased with depth. This explanation was lacking in the above mentioned papers and could be useful for future chamber designs.

1.7 Scope of this thesis work

The scope of this work can be divided into 4 main parts. Part 1 is the MC modeling and energy tuning of the electron beam source against measured PDD curves in water. Three linear accelerators (linac) provide the electron beams used in this work. The first is the Varian CL2300C/D clinical linac for the nominal electron energies 6, 9, 12, 15, and 18 MeV and the second is the Varian CL21EX clinical linac for the nominal electron energy 4 MeV. Both are based at the Montreal General Hospital (Montreal, Canada). The third linac is the NPL’s Radiation Dynamics Ltd research linac (Teddington, UK). Tuning of the NPL’s linac for the nominal energies 4, 6, 8, 10, 12, 16, and 19 MeV was already performed in an earlier work (Zakikhani
2006). Part 2 is the MC modeling and tuning of the NACP-02 chamber by comparing simulated backscatter factors (BSF) to measured backscatter factors. BSF values for water, graphite, aluminum, and copper with respect to air were investigated for the Varian linacs 4 – 18 MeV. Part 3 is the calculation of the mean Spencer-Attix mass restricted collisional stopping-power ratios water-to-air, $s_{\text{w,air}}$, and graphite-to-air, $s_{\text{g,air}}$, using Monte Carlo for all the linac energies. Finally, part 4 is the calculations of electron perturbation correction factors for all the linac energies, in graphite and water phantoms, at depths ranging from $z_{\text{ref}}$ to $R_{50}$ using Monte Carlo. Part 4 will also include analysis of the effect of different chamber components on the value of the perturbation correction factors.
Chapter 2 Literature Review

2.1 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber in water

For well guarded plane-parallel ionization chambers, current absorbed dose protocols such as the AAPM’s TG-51 and the IAEA’s TRS-398 assume a value of unity for megavoltage electron perturbation correction factors used in the calculation of $k_{Q,Q_0}$ factors. However, much research has been published that has shown the contrary. As discussed in chapter 1, the perturbation correction factors of interest for plane-parallel ionization chambers such as the NACP-02 chamber, are $p_Q$, $p_{cav}$ and $p_{wall}$. This section of the literature review will be limited to papers dealing with electron perturbation correction factors for the NACP-02 chamber.

The $p_{wall}$ perturbation correction factor has been more extensively studied than the $p_{cav}$ perturbation correction factor. Two recent papers published in the last year on $p_{wall}$ values for the NACP-02 chamber were by Verhaegen et al (2006) and Buckley and Rogers (2006). Verhaegen et al studied $p_{wall}$ values in water at depths from the buildup region to $R_{50}$ for the 4 – 19 MeV electron beams of the NPL linac and for the 6 – 18 MeV clinical electron beams from a Varian CL2300C/D linac using the Monte Carlo (MC) code EGSnrc. Their MC electron beam source models were validated against measurements of PDD curves in water and the energy spectrum and electron angular distribution were extracted from the phase-space files. The MC NACP-02 chamber model was validated against backscattering measurements. Mean Spencer-Attix mass restricted collisional stopping power ratios water-to-air, $s_{w,air}$, were also calculated using Monte Carlo rather than relying on the Burns equations (eq. 1.10 and 1.11). Transport cutoff values were 521 keV for electrons and 10 keV for photons.
Buckley and Rogers studied $p_{\text{wall}}$ values in water mainly at depth $z_{\text{ref}}$ for electron energies 6 – 25 MeV produced by a mixture of linacs: Varian, Therac 20, Philips SL75-20, Siemens KD2, and Racetrack MM50. $p_{\text{wall}}$ was also studied at depths from the buildup region to $R_{50}$ for the 6 MeV Varian electron beam and the 20 MeV Therac 20 electron beam. Incident electron beam spectra were taken from work by Ding and Rogers (1995). Dose calculations were performed using the Monte Carlo EGSnrc user code CSnrc. This code employs correlated sampling as a variance reduction technique that improves efficiency by a factor of 3 – 4 over the EGSnrc user code CAVRznrc. Parallel-plate chambers studied included the NACP-02, the Markus, the Roos, and the PS-033. The MC chamber models were not validated against any experimental measurements. Transport cutoffs were 521 keV for electrons and 10 keV for photons.

The $p_{\text{wall}}$ results of Verhaegen et al are similar to those obtained by Buckley and Rogers. At $z_{\text{ref}}$, Verhaegen et al found that $p_{\text{wall}}$ for the NACP-02 chamber varied from 1.016 – 1.010 for electron beams with $R_{50}$ values ranging from 2.45 – 7.73 cm (Varian CL2300C/D, 6 – 18 MeV). Buckley and Rogers calculated at $z_{\text{ref}}$ that $p_{\text{wall}}$ varied from 1.018 – 1.008 for electron beams with $R_{50}$ values ranging from 2.63 – 7.72 cm (Varian 6 – 18 MeV). At depths between $z_{\text{ref}}$ and $R_{50}$, Verhaegen et al noted a 6.8% increase in $p_{\text{wall}}$ value for the 6 MeV Varian beam and a 2.8% increase for the 18 MeV Varian beam. Buckley and Rogers found slightly smaller increases of close to 5% for their 6 MeV Varian beam and 2.3% for their 20 MeV Therac 20 beam. Differences in NACP-02 chamber model likely caused the greater discrepancies in results at $R_{50}$ due to that depth being in a high gradient region of the PDD curve. In accordance with the TG-51 dosimetry protocol, neither Verhaegen et al nor Buckley and Rogers accounted for the water equivalent thickness of the NACP-02 graphite front window when determining the depths of the effective points of measurement.

Besides Verhaegen et al (2006), $p_{\text{wall}}$ values at $z_{\text{ref}}$ for the 4 – 19 MeV electron beams of the NPL linac were also calculated by Williams et al (1998). Verhaegen et al found that $p_{\text{wall}}$ exceeded unity by 1.2% for the 19 MeV beam and up to 2.3% for
the 4 MeV NPL beam. Williams et al found smaller variations of 0.65% for the 19 MeV beam and 1.27% for the 4 MeV beam. For the latter, particles incident on the phantom came from phase space files 10 cm in front of the phantom created by simulations of the linac head. It should be noted that Williams et al used the Monte Carlo code EGS4 which is less accurate than the EGSnrc code used by Verhaegen et al. Results obtained by EGS4 have a strong dependence on electron step-size. This flaw was corrected in EGSnrc (Kawrakow 2000). As well, Williams et al used transport cutoffs of 521 keV for electrons only in certain regions near the dose scoring region and everywhere else was set to 711 keV.

The perturbation in electron fluence caused only by the NACP-02 graphite back wall at $z_{ref}$ for the NPL linac electron beams was investigated by McEwen et al (2006) and Verhaegen et al (2006). Extra focus was given to the back wall because it was widely believed that electrons back scattering from the back wall was the main source of perturbation for $p_{wall}$. McEwen et al developed an empirical method to calculate the back wall effects, $p_{backwall}$, based on graphite backscattering data. They found that $p_{backwall}$ ranged from 1.014 to 1.005 for the 4 – 19 MeV electron beams.

Verhaegen et al took an approach different to McEwen et al to study the effects of the back wall. Where McEwen et al ignored the effects of the front and side walls, focusing only on the presence of the graphite backing, Verhaegen et al focused on the absence of the graphite backing by replacing it with water. With only the NACP-02 chamber’s front and side walls present, the $p_{wall}$ value decreased by 1.3% from 1.023 to 1.010 for the 4 MeV beam and by 0.7% from 1.012 to 1.005 for the 19 MeV beam. The fact that the difference from unity was only cut in half with the replacement of the back wall with water indicates that significant perturbation is also being caused by the front and/or side walls of the chamber and can not be ignored as some have assumed.

The isolated effects of the side, front and back walls of the NACP-02 chamber can not be summed to produce the overall $p_{wall}$ value because there is likely some
interaction between the walls that could increase or decrease the perturbation. However, one can estimate from the decreases seen in $p_{wall}$ by Verhaegen et al when the back wall was replaced with water that the $p_{backwall}$ values range somewhere from 1.013 to 1.007 for the electron energies 4 – 19 MeV. This range is very similar to that empirically calculated by McEwen et al.

Electron fluence perturbation caused by the air cavity, $p_{cav}$, in the NACP-02 chamber for electron beams 4 – 19 MeV has been studied using Monte Carlo methods by Ma and Nahum (1994), Williams et al (1998), and Verhaegen et al (2006). Within statistical uncertainty, Ma and Nahum found that $p_{cav}$ values at $z_{max}$ were unity. $z_{max}$ represents the depth at 100% PDD. They used particle energy transport cutoffs of 1 keV. Williams et al found that $p_{cav}$ values at $z_{ref}$ were also within unity. Verhaegen et al, on the other hand, found $p_{cav}$ values at $z_{ref}$ to be significantly below unity by 0.4 – 0.8% but with no clear energy dependence. The $p_{cav}$ values of Verhaegen et al are considered more accurate as the calculations were performed with the Monte Carlo code EGSnrc while Williams et al and Ma and Nahum both used EGS4.

Reft and Kuchnir (1991) experimentally investigated $p_{cav}$ values for the NACP-01 and Markus chambers at $z_{max}$ in an acrylic phantom and for the Holt, Capintec, and Exradin chambers at $z_{max}$ in a polystyrene phantom by an in-phantom dose comparison with a Farmer-type cylindrical chamber. The method was described by Casson and Kiley (1987). The matching cylindrical chambers were an acrylic wall (PTW) chamber and a polystyrene wall (EXR) chamber. Nominal electron energies were 5.5, 6, 9, 12, 15, 18 and 22 MeV from a Varian CL2500 linear accelerator. Source to phantom surface distance was 100 cm and the field size at the phantom surface was 10 x 10 cm$^2$. The measured $p_{cav}$ values for the NACP-01 chamber were energy independent. The average value for the NACP-01 was 0.980 with a standard deviation of 0.5% and an overall uncertainty of 1%. Although measured in an acrylic phantom, the energy independence of the $p_{cav}$ values for the NACP-01 chamber is consistent with the observations of Ma and Nahum, Williams et al and Verhaegen et al.
Reft and Kuchnir (2000) also experimentally investigated the overall perturbation correction factors, $p_Q$, for the NACP chamber at depths $z_{\text{max}}$, $d_{90}$ and $d_{80}$ in a solid water phantom by equating the percentage depth doses measured with the NACP chamber to those measured with a PTW diamond detector model 60003. The depths $z_{\text{max}}$, $d_{90}$, and $d_{80}$ correspond to PDD values of 100%, 90%, and 80% respectively. The diamond detector was assumed to be energy independent with a $p_Q$ value of unity at all measurement depths. Nominal electron energies used were the 6, 12, 16 and 20 MeV beams produced by the Varian CL2100C linac. Source to phantom surface distance was 100 cm and the field size was 15 x 15 cm$^2$. The $p_Q$ results for the NACP chamber were remarkably constant with an average of 1.000 ± 0.005. However, the estimated uncertainty on this value was 1.3%. These results were for solid water but were expected to hold in water as well.

The $p_Q$ values of the NACP-02 chamber were also studied using Monte Carlo simulations by Williams et al (1998) and Verhaegen et al (2006). While Verhaegen et al calculated $p_{\text{wall}}$ factors that were approximately 0.4 – 1% greater than those of Williams et al, they also calculated $p_{\text{cav}}$ values that were approximately 0.4 – 0.8% smaller than those of Williams et al. The result is that Verhaegen et al and Williams et al calculated within 1 standard deviation uncertainty $p_Q$ values in the same range, (1.0150 ± 0.13% – 1.0044 ± 0.13%) and (1.013 ± 0.12% -1.0072 ± 0.38%) respectively for energies 4 – 19 MeV despite using the different Monte Carlo codes, EGSnrc and EGS4. Clearly the assumption of unity for electron perturbation correction factors in the absorbed dose protocols needs to be revisited.

2.2 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber in graphite

Electron perturbation correction factors in graphite for plane-parallel ionization chambers are not as widely studied as those in water as measurements in
graphite are less commonly performed. However as discussed in chapter 1, perturbation factors in graphite play an important role in dose transfer technique used by the NPL. Williams et al (1998) studied $p_{cav}$, $p_{wall}$ and $p_Q$ for the NACP-02 chamber at $z_{ref}$ in a graphite phantom for the NPL electron beams 4 – 19 MeV. For the 4 – 19 MeV beams, $p_{cav}$ values ranged from 0.9969 ± 0.28% down to 0.9949 ± 0.43%, $p_{wall}$ values ranged from 1.0268 ± 0.27% down to 1.0124 ± 0.47%, and $p_Q$ values ranged from 1.0237 ± 0.20% down to 1.0072 ± 0.31%. These results, however, may be out dated because of potentially inadequate transport energy cutoffs and the use of the EGS4 code which has known problems with ionization chamber response.

Nilsson et al (1997) studied only the $p_{wall}$ factors for electron beams 5 – 20 MeV at $z_{max}$ in a graphite phantom. Their $p_{wall}$ values were measured experimentally using the BPPC-1 broad plane-parallel ionization chamber to simulate only the front and back walls of commercial chambers such as the NACP-02, the Attix 449 model, and the PTW Roos. The values of $p_{wall}$ for the NACP-02 chamber ranged from 1.002 for the lowest energy to 1.004 for the highest energy. These results do not take into account the chamber’s rexolite side walls which can have a significant impact on the $p_{wall}$ values.

With the availability of the Monte Carlo code EGSnrc that corrects many of the flaws of EGS4 and faster computing power, there is an opportunity now to calculate electron perturbation correction factors in graphite for the NACP-02 chamber using the full chamber geometry with much lower electron energy transport cutoffs and lower energy thresholds for secondary particle production.
Chapter 3 Materials and Methods

3.1 Validation of the CL21EX and CL2300C/D Varian linac BEAMnrcMP Monte Carlo models

Electron perturbation correction factors of the NACP-02 plane-parallel chamber in graphite and water phantoms were calculated for the electron beams generated by the CL2300C/D and CL21EX Varian linacs and the Radiation Dynamics Ltd linac of the NPL (hereby referred to as the ‘NPL linac’). As the NPL linac for nominal electron energies 4, 6, 8, 10, 12, 16, and 19 MeV had already been modelled and validated recently (Zakikhani 2006), only the CL2300C/D linac for nominal electron energies 6, 9, 12, 15, and 18 MeV and the CL21EX linac for nominal electron energy 4 MeV needed to be modelled and validated. The Varian linac models were based on previous work by Huang et al (2005) who performed extensive investigations into beam profiles, thus only electron energy tuning against PDD curves measured in water was done in this work.

The PDD measurements were made with an EFD electron diode detector in a RFA-300 water tank, both manufactured by Scanditronix. The water tank has a scanning volume of 50 cm x 50 cm x 50 cm, a position reproducibility of ± 0.1 mm, a positioning accuracy of ± 0.5 mm, and a scanning resolution of 0.2 to 500 mm. Silicon-to-water stopping power ratios were not used to correct the diode measurements as Wang and Rogers (2007) have shown that the diode response per unit dose to water is constant as a function of electron beam energy and depth.

The linac models were built using BEAMnrcMP (Rogers et al 2006) which is based on the EGSnrcMP code system. The convenience of BEAMnrcMP is that component modules are available that allow an accelerator to be easily built section by section. Figure 3.1 shows the BEAMnrcMP model built based on the
manufacturer’s specifications for the CL21EX and CL2300C/D Varian linacs. The labels in parentheses denote the name of the component modules used.

![Figure 3.1 BEAMnrcMP model used for the Varian linacs: CL21EX and CL2300C/D.](image)

In the Monte Carlo simulations, ECUT and PCUT, the cut-off energy levels below which electron and photon transport cease resulting in local deposition of the entire particle’s energy, were set to 0.521 MeV and 0.01 MeV respectively. AE and AP are the low-energy thresholds for the production of knock-on electrons and secondary Bremsstrahlung photons. The value of AE was 0.521 MeV and AP was 0.01 MeV. The value for ESAVE_GLOBAL, the maximum charged particle energy
at which range rejection is considered was 2 MeV. Spin correction of elastic scattering was used as well as PRESTA II for the electron step algorithm and EXACT for the boundary crossing algorithm. PRESTA II is the more accurate algorithm implemented in EGSnrcMP/EGSnrc that corrects for the underestimations of PRESTA I (EGS4) in calculating lateral and longitudinal corrections to account for elastic scattering in a condensed history electron step. EXACT causes electrons to be transported across region boundaries in single elastic scattering mode as soon as they are within a given distance from the boundary. Spin correction, PRESTA II, and EXACT can all have significant impact on the accuracy of the simulation results. They will therefore also be used in the backscatter factor calculations (section 3.2), the stopping power calculations (section 3.3), and the perturbation factor calculations (section 3.4 and 3.5).

All measurements and simulations with the Varian linacs were for a SSD of 100 cm. For nominal electron energies 4 – 9 MeV, the field size was 10 cm x 10 cm and for nominal electron energies 12 – 18 MeV, the field size was 15 cm x 15 cm. For each electron beam, the energy of the monoenergetic divergent point source used in the Monte Carlo simulations was tuned with the goal that the $R_{50}$ of the measured and simulated water PDD curves would match within less than 1 mm and the water PDD curves at any given depth would be within 2%.

Figure 3.2 displays the BEAMnrcMP model for the NPL linac (Zakikhani 2006). Its design is much simpler than that of the clinical Varian linacs and is mainly used for research and calibration purposes. The single scattering foil produces less photon contamination than the dual scattering foils in the Varian linacs and the SSD is 200 cm as opposed to 100 cm.
3.2 Validation of the NACP-02 Monte Carlo model

The NACP-02 plane-parallel chamber is commonly used in electron dosimetry. Its cylindrical shape has a total diameter of 3 cm and a height of 1 cm. The chamber air cavity is 2 mm thick with an active volume diameter of 1 cm surrounded by a 3 mm guard ring. The thin front window is composed of a mylar foil and a graphite electrode with a combined mass thickness of 104 mg/cm². The chamber also has a thick graphite backing and is housed in a rexolite casing (figure 3.3). Rexolite, also known as rexolite 1420 (William Brand-Rex Division, Concord, MA), is a cross linked styrene copolymer with high electrical resistance and density similar to polystyrene.

Once the linac energies were properly tuned, phase-space files were collected at either a SSD of 100 cm for the Varian linacs or 200 cm for the NPL linac.
Based on detailed confidential specifications of the NACP-02 chamber provided by the manufacturer Scanditronix, a Monte Carlo model of the chamber was built using the EGSnrcMP user code CAVRZnrc (Rogers et al 2005). CAVRZnrc simulates electron and photon transport in a finite, right cylindrical geometry allowing among other things, the scoring of dose in specified regions. CAVRZnrc was used as opposed to DOSRZnrc, a code similar in function, because CAVRZnrc possesses an extra feature in its electron range rejection algorithm that allows range rejection to be performed with respect to the chamber air cavity. This greatly reduces computational time if our interest is only in the dose deposited in the air cavity rather than the whole geometry. Figure 3.4 below shows the Monte Carlo model of the chamber.

Figure 3.3 Cross-section view of the NACP-02 plane-parallel ionization chamber (Williams et al 1998).
To validate the Monte Carlo chamber model, backscatter factors were measured and compared to the simulated backscatter factors obtained with CAVRZnc. This is important as often the specifications released by the manufacturer are not as detailed as required.

The backscatter experiments were performed using the Varian linacs CL2300C/D (6, 9, 12, 15, and 18 MeV) and CL21EX (4 MeV). In the experimental setup, the electron beam was pointing upwards and the applicator was 10 cm x 10 cm for the beam energies 4-9 MeV and 15 cm x 15 cm for the beam energies 12–18 MeV (figure 3.5). The phantom material was PMMA for electron beam energies 4 -12 MeV and Solid Water™ for energies 15 and 18 MeV. The bottom of the phantom was at SSD 100 cm. The NACP-02 chamber was embedded in the phantom with its front window flush with the top surface of the phantom. For all energies except 4 MeV, the water equivalent thickness of the phantom buildup and chamber backing corresponded to $z_{max}$ in water. In the case of the 4 MeV electron beam, no phantom buildup material was used as the chamber backing already amounted to a water
equivalent thickness in the 70 % region of the water PDD tail. Various thicknesses, $t$, of backscatter material (copper, aluminum, water and graphite) were placed on top of the chamber front window.

![Diagram of backscatter experimental setup]

**Figure 3.5** Backscatter experimental set-up. a) Schematic diagram of backscatter experimental setup. b) Backscatter setup on CL2300C/D with aluminum backscatter plate. c) Backscatter setup on CL21EX with water container on top.

The purity of the copper plates was 99.9% while that of the aluminum was 99%. The density of the graphite backscatter plates was 1.84 g/cm$^3$. The cylindrical
water container (figure 3.3c) was approximately 15 cm in diameter and 10 cm in height. The hollow cylindrical tube was made of PMMA and its top and bottom were sealed with mylar.

The experimentally measured backscatter factor (BSF) was calculated as:

\[ BSF_{\text{meas}} = \frac{Q_{\text{backscatter_plate}}}{Q_{\text{air_backing}}} \]  \hspace{1cm} (3.1)

\( Q_{\text{backscatter_plate}} \) and \( Q_{\text{air_backing}} \) are the respective measured charge with the backscatter material on top of the chamber window and the measured charge with no backscatter material. Measurements were not corrected for the polarity effect as several test cases revealed the effect on BSF values to be less than 0.05%. The Monte Carlo backscatter factor calculated using CAVRZnrc was defined as:

\[ BSF_{\text{MC}} = \frac{D_{\text{backscatter_plate}}}{D_{\text{air_backing}}} \]  \hspace{1cm} (3.2)

\( D_{\text{backscatter_plate}} \) is the dose to the active scoring volume of the chamber when there is backscatter material on top of the chamber window and \( D_{\text{air_backing}} \) is the dose when no backscatter material is present. In the CAVRZnrc simulations, the full phase-space files collected from BEAMnrcMP were used. ECUT was 0.512 MeV and PCUT was 0.001 MeV in the dose scoring region and its immediate surrounding regions. For all other regions outside of this volume, ECUT was 0.521 MeV and PCUT was 0.01 MeV. The goal of these transport cutoff settings was to have the highest accuracy possible for the dose calculated in the region of interest while keeping the simulation CPU time reasonable.
3.3 Calculation of stopping power ratios

Both water-to-air \((s_{w,\text{air}})\) and graphite-to-air \((s_{g,\text{air}})\) mean Spencer-Attix mass restricted collisional stopping power ratios (hereby referred to as Spencer-Attix stopping power ratios) for all electron beam energies studied were calculated using the Monte Carlo EGSnrcMP user code SPRRZnrc. This is because in the case of \(s_{w,\text{air}}\), it is more accurate than the Burns equations (Rogers 2004), and for \(s_{g,\text{air}}\), no previous data has been published. SPRRZnrc calculates Spencer-Attix stopping power ratios in each region of a right cylindrical geometry with an on-the-fly scoring technique (Rogers et al 2005). As is accepted in current protocols, the particle transport energy cutoff was set to 10 keV. The CSDA range for this energy corresponds to the mean chord length of 2.6 mm for the NACP-02 chamber’s 2 mm thick air cavity (Mainegra-Hing et al 2003). The full phase-space files from BEAMnrcMP were used as the electron beam sources.

3.4 Calculation of water and graphite electron perturbation correction factors for the NACP-02 plane-parallel chamber at depths between \(z_{\text{ref}}\) and \(R_{50}\)

Electron perturbation correction factors in water were calculated for the Varian linacs 4-18 MeV at depths \(z_{\text{ref}}\) and \(R_{50}\). The graphite electron perturbation correction factors were calculated for both the Varian linacs for depths ranging between \(z_{\text{ref}}\) and \(R_{50}\) and the NPL linac 4-19 MeV for depths only at \(z_{\text{ref}}\). The density of the graphite phantom was 1.77 g/cm\(^3\). The Monte Carlo calculations were done using the EGSnrcMP user code DOSRZnrc (Rogers et al 2005). Like CAVRZnrc, DOSRZnrc simulates electron and photon transport in a finite, right cylindrical geometry. DOSRZnrc was used instead of CAVRZnrc because it has an extra feature in the Monte Carlo inputs that allows not only the total dose of each region to be outputted but also gives the fraction of the total dose due to electrons entering from the front, side, and back walls of the region. This extra information could be useful in
analyzing the influence of different chamber parts on the wall perturbation correction factor, $p_{\text{wall}}$.

To calculate the perturbation correction factors in water, $p_Q$, $p_{\text{cav}}$, and $p_{\text{wall}}$, 3 separate Monte Carlo simulations were performed according to the geometries shown in figure 3.6.

**Figure 3.6** The three geometry setups modelled in DOSRZnrc for the calculations of $p_Q$, $p_{\text{cav}}$, and $p_{\text{wall}}$ (Verhaegen et al 2006).

In figure 3.6 (a), the entire NACP-02 chamber geometry consists of water. Dose to water was scored in the thin dotted region indicated by the arrow. The effective point of measurement was in the middle of the dotted region. To avoid volume averaging of the dose, the thickness of the thin dotted region was such that the dose variation with depth in it was no more than 0.1 %. In figure 3.6 (b), the entire chamber geometry consists of water except for the air cavity and in figure 3.6 (c), the full NACP-02 chamber geometry is modelled with the appropriate wall materials.
For both figures 3.6 (b) and (c), dose to air was scored in the dotted regions corresponding to the sensitive volume of the chamber and the effective point of measurement was the inside centre of the front chamber window. Following the format of Verhaegen et al (2006) and Buckley and Rogers (2006), no scaling for the water equivalent thickness of the chamber front graphite window was performed (figure 3.6c). This meant that for any calculation, the effective point of measurement of figures 3.6 (b) and (c) were at the same depth. The figures 3.6 (a), (b), and (c) as described will henceforth be referred to case a, case b, and case c respectively. Using the calculated doses from these three cases, the perturbation factors are calculated as follows:

\[ P_{\text{cav}} \times (s_{w,\text{air}}) = \frac{D_a}{D_b}, \]  
\[ P_{\text{wall}} = \frac{D_b}{D_c}, \]  
\[ P_Q \times (s_{w,\text{air}}) = \frac{D_c}{D_e}. \]

The calculations for the electron perturbation correction factors of the NACP-02 chamber in graphite is exactly the same as just described for water except with all water regions replaced with graphite and with \( s_{g,\text{air}} \) replacing \( s_{w,\text{air}} \) in equations 3.3 and 3.5.

Similar to the CAVRZnrc simulations, the DOSRZnrc simulations used an ECUT of 0.512 MeV and a PCUT of 0.001 MeV in the dose scoring region and its immediate surrounding regions to obtain the most precise dose calculations. All other regions used an ECUT of 0.521 MeV and a PCUT of 0.01 MeV. The maximum energy at which electron range rejection was considered was 1.25 MeV.

Nearly all calculations were performed on the computer cluster of the medical physics department at McGill University while a few were performed by the NPL on
their distributed computer grid. Besides the advantage of having extra computing power from the NPL, the source used by the NPL was a full beam simulation rather than a phase-space file. A full beam simulation source is considered more accurate than a phase-space file source since it avoids the over sampling problems of the latter. As calibration and reference dosimetry occur at $z_{ref}$, the perturbation correction factors at $z_{ref}$ in graphite for both the Varian linacs and NPL linac were calculated by the NPL. The NPL simulations were run until the standard deviation on the mean for the calculated dose was 0.2% or better. In the interest of time constraints, all other calculations were done on the McGill cluster using the linac full phase-space files collected from BEAMnrcMP. These simulations used 1.5 billion particles each from the phase-space files to achieve a standard deviation on the mean for the calculated dose between 0.15% and 0.27%.

3.5 Other investigations in water and graphite electron perturbation correction factors for the NACP-02 plane-parallel chamber

In previous work (Verhaegen et al 2006), $p_{cav}$ and $p_{wall}$ in water were shown to increase with depth in the phantom but no thorough investigation into the cause was done. In the same work, only a short investigation into the effect of the chamber back wall on $p_{wall}$ at $z_{ref}$ in water was performed. It was concluded that the chamber back wall had a significant effect on $p_{wall}$ in water but the effects of the side or front walls were not studied. To gain a more thorough understanding of the results obtained by Verhaegen et al, three separate investigations were included in this thesis in addition to the work of section 3.4.

The first investigation was into why $p_{wall}$ increases with depth in water. It was vaguely hypothesized by Verhaegen et al that the wider angular distribution and lower mean energy of electrons at deeper depths was somehow the cause. This hypothesis was tested by building the NACP-02 chamber model in BEAMnrcMP
using the FLATFILT component module and setting LATCH numbers in the various chamber regions (figure 3.7).

![Figure 3.7 Right cylindrical geometry of the BEAMnrcMP NACP-02 chamber model](image)

BEAMnrcMP was used as opposed to CAVRZnrc or DOSRZnrc as it allows the scoring of phase-space files. In our BEAMnrcMP chamber model, a phase-space file was scored right after the air cavity for case b and case c. The ECUT and PCUT settings were the same as those used during the CAVRZnrc (section 3.2) and the DOSRZnrc (section 3.4) calculations. The particle source was the full phase-space files collected from the linac simulations in BEAMnrcMP. Simulations were run for the BEAMnrcMP chamber model using the 6 and 18 MeV CL2300C/D linac beams, at $z_{ref}$ and $R_{50}$ in the water phantom. Angular distribution and energy spectrum of the electrons was extracted from the chamber collected phase-space files using BEAMDP (Ma and Rogers 2007). BEAMDP is short for BEAM Data Processor computer program and it can be used to analyze phase-space parameters of radiation beams.
generated by BEAMnrcMP as well as derive data needed for use in Monte Carlo radiotherapy treatment planning.

The second investigation was into the significance of the side, back, and front NACP-02 chamber walls on the value of $p_{wall}$. To determine the effect of the different chamber walls, $p_{wall}$ was recalculated with essentially the same setup as in figure 3.6 except that for case c, the phantom material replaced either the chamber back wall (figure 3.8) or the chamber side wall (figure 3.9) or the chamber front wall (figure 3.10) depending on whether we were studying the effects of the back wall, side wall, or front wall. Wall effects were investigated for the 6 and 18 MeV CL2300C/D linac beams, at $z_{ref}$ and $R_{50}$, in both water and graphite phantoms.

Figure 3.8 Right cylindrical geometry of the DOSRZnrc NACP-02 chamber model with the chamber back wall replaced with the phantom material
Finally the third investigation was into why $p_{cav}$ increases with depth. To isolate whether it is the forward charged particle fluence or the backscattered charged...
particle fluence having the greater effect on $p_{cav}$, perturbation correction factor calculations in DOSRZnrc for both water and graphite, at $z_{ref}$ and $R_{50}$, were performed for the 6 and 18 MeV CL2300C/D beams with the same setup as in figure 3.6, except everything behind the dose scoring region was set to vacuum. These simulations were also performed using the BEAMnrcMP chamber model to obtain angular distribution and energy spectrum information from phase-space files collected just behind the air cavity.
Chapter 4 Results and Discussion

4.1 Validation of the CL21EX and CL2300C/D Varian linac BEAMnrcMP Monte Carlo models

The characteristics of the measured and MC tuned CL21EX and CL2300C/D Varian linac electron beams in water are shown in table 4.1. The $R_{50}$ values of the measured and MC simulated electron beams matched within 0.05 cm or less. Figures 4.1 to 4.6 display the measured water PDD curves with their respective MC generated PDD curves for electron energies 4-18 MeV. For the 4 MeV electron beam (figure 4.1), the largest difference between the measured and MC simulated PDD curves was approximately 3% in the buildup region. Beyond the buildup region, the 4 MeV PDD curves matched within 2%. For the 6 and 15 MeV electron beams (figure 4.2 and figure 4.5), the simulated PDD curves were within 1% or better of their measured PDD curves over the entire range of depth. For the 9, 12, and 18 MeV electron beams (figures 4.3, 4.4, and 4.6), the match between simulated and measured PDD curves was 1.5% or better over the entire range of depth. Large differences between the measured and simulated $z_{max}$ values at higher electron energies are not significant as the higher energy PDD curves are fairly flat near the max 100% PDD value.

<table>
<thead>
<tr>
<th>Linac Energy (MeV)</th>
<th>water $z_{max}$ (cm)</th>
<th>water $R_{50}$ (cm)</th>
<th>water $z_{ref}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal energy</td>
<td>MC tuned energy</td>
<td>measured</td>
<td>MC measured</td>
</tr>
<tr>
<td>4</td>
<td>4.15</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>6.85</td>
<td>1.42</td>
<td>1.43</td>
</tr>
<tr>
<td>9</td>
<td>9.81</td>
<td>2.16</td>
<td>2.17</td>
</tr>
<tr>
<td>12</td>
<td>13.25</td>
<td>2.89</td>
<td>2.96</td>
</tr>
<tr>
<td>15</td>
<td>16.80</td>
<td>3.39</td>
<td>3.54</td>
</tr>
<tr>
<td>18</td>
<td>19.97</td>
<td>2.10</td>
<td>2.78</td>
</tr>
</tbody>
</table>

Table 4.1 Characteristics of electron beams in water produced by the CL21EX (4 MeV) and the CL2300C/D (6-18 MeV) linacs. $z_{ref}$ was calculated using eqn 1.2.
Figure 4.1 Measured and calculated water PDD curves for the 4 MeV CL21EX electron beam

Figure 4.2 Measured and calculated water PDD curves for the 6 MeV CL2300C/D electron beam
Figure 4.3 Measured and calculated water PDD curves for the 9 MeV CL2300C/D electron beam

Figure 4.4 Measured and calculated water PDD curves for the 12 MeV CL2300C/D electron beam
4.1 Validation of the Varian linac Monte Carlo models

**Figure 4.5** Measured and calculated water PDD curves for the 15 MeV CL2300C/D electron beam

**Figure 4.6** Measured and calculated water PDD curves for the 18 MeV CL2300C/D electron beam
Using the Varian linac Monte Carlo models that were tuned against water PDD measurements, the electron beam characteristics for the energies 4 – 18 MeV in graphite (1.77 g/cm³) were simulated (table 4.2).

<table>
<thead>
<tr>
<th>nominal energy (MeV)</th>
<th>MC tuned energy (MeV)</th>
<th>MC graphite z_max (cm)</th>
<th>MC graphite R_{50} (cm)</th>
<th>MC graphite z_ref (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.15</td>
<td>0.50</td>
<td>0.88</td>
<td>0.43</td>
</tr>
<tr>
<td>6</td>
<td>6.85</td>
<td>0.93</td>
<td>1.57</td>
<td>0.84</td>
</tr>
<tr>
<td>9</td>
<td>9.81</td>
<td>1.41</td>
<td>2.36</td>
<td>1.32</td>
</tr>
<tr>
<td>12</td>
<td>13.25</td>
<td>1.91</td>
<td>3.24</td>
<td>1.84</td>
</tr>
<tr>
<td>15</td>
<td>16.80</td>
<td>2.31</td>
<td>4.15</td>
<td>2.39</td>
</tr>
<tr>
<td>18</td>
<td>19.97</td>
<td>2.45</td>
<td>4.93</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Table 4.2 Characteristics of electron beams in graphite produced by the CL21EX (4 MeV) and the CL2300C/D (6-18 MeV) linacs. z_{ref} was calculated using eqn 1.2.

The characteristics in water of the NPL Monte Carlo electron beam model previously validated by Zakikhani (2006) are shown in table 4.3. Using the same NPL model, the electron beam characteristics for the energies 4 – 19 MeV in graphite were simulated (table 4.4).

<table>
<thead>
<tr>
<th>nominal energy (MeV)</th>
<th>MC tuned energy (MeV)</th>
<th>MC water z_max (cm)</th>
<th>MC water R_{50} (cm)</th>
<th>MC water z_{ref} (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.97</td>
<td>0.73</td>
<td>1.29</td>
<td>0.67</td>
</tr>
<tr>
<td>6</td>
<td>5.90</td>
<td>1.23</td>
<td>2.07</td>
<td>1.14</td>
</tr>
<tr>
<td>8</td>
<td>8.06</td>
<td>1.81</td>
<td>2.97</td>
<td>1.68</td>
</tr>
<tr>
<td>10</td>
<td>9.76</td>
<td>2.24</td>
<td>3.66</td>
<td>2.10</td>
</tr>
<tr>
<td>12</td>
<td>11.61</td>
<td>2.70</td>
<td>4.42</td>
<td>2.55</td>
</tr>
<tr>
<td>16</td>
<td>15.45</td>
<td>3.57</td>
<td>5.94</td>
<td>3.46</td>
</tr>
<tr>
<td>19</td>
<td>17.99</td>
<td>4.01</td>
<td>6.96</td>
<td>4.08</td>
</tr>
</tbody>
</table>

Table 4.3 Characteristics of electron beams in water produced by the NPL linac (Zakikhani 2006). z_{ref} was calculated using eqn 1.2.
4.2 Validation of the Monte Carlo model for NACP-02 plane parallel ionization chamber with backscatter factors

Relative backscatter factors (BSF) calculated using a MC NACP-02 chamber model based on the manufacturer’s specifications were systematically greater than the measured BSF values by 1-3%. Varying many different parts of the chamber were considered but due to limits on computing power, only tuning of the chamber’s front window thickness and density of the chamber’s graphite walls were performed as these two factors most likely had the greatest impact on simulation results. Graphite density was increased by 6% while the thickness of the front window’s mylar foil and graphite electrode were increased by 10% and 40% respectively. These adjustments greatly improved the agreement between calculated and measured BSF values to within 1%, 0.5%, 0.36% and 0.36% for copper, aluminum, graphite and water, respectively for the Varian linac energies 6 – 18 MeV. In other words, all measured and simulated BSF values for water and graphite matched within 1 standard deviation while results for the aluminum and copper BSF values were within 1 – 2 standard deviations. BSF results after chamber tuning are shown in figures 4.7 – 4.14 with error bars of 1 standard deviation.

<table>
<thead>
<tr>
<th>nominal energy (MeV)</th>
<th>MC tuned energy (MeV)</th>
<th>MC graphite $z_{max}$ (cm)</th>
<th>MC graphite $R_{50}$ (cm)</th>
<th>MC graphite $z_{ref}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.97</td>
<td>0.48</td>
<td>0.84</td>
<td>0.41</td>
</tr>
<tr>
<td>6</td>
<td>5.90</td>
<td>0.81</td>
<td>1.35</td>
<td>0.71</td>
</tr>
<tr>
<td>8</td>
<td>8.06</td>
<td>1.18</td>
<td>1.93</td>
<td>1.06</td>
</tr>
<tr>
<td>10</td>
<td>9.76</td>
<td>1.46</td>
<td>2.37</td>
<td>1.32</td>
</tr>
<tr>
<td>12</td>
<td>11.61</td>
<td>1.76</td>
<td>2.86</td>
<td>1.61</td>
</tr>
<tr>
<td>16</td>
<td>15.45</td>
<td>2.31</td>
<td>3.83</td>
<td>2.20</td>
</tr>
<tr>
<td>19</td>
<td>17.99</td>
<td>2.59</td>
<td>4.39</td>
<td>2.54</td>
</tr>
</tbody>
</table>

Table 4.4 Characteristics of electron beams in graphite produced by the NPL linac. $z_{ref}$ was calculated using eqn 1.2.
Figure 4.7 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for water backing in the 6, 12, and 18 MeV Varian CL2300C/D electron beams.

Figure 4.8 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for water backing in the 9 and 15 MeV Varian CL2300C/D electron beams.
Figure 4.9 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for graphite backscatter plates in the 6, 12, and 18 MeV Varian CL2300C/D electron beams.

Figure 4.10 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for graphite backscatter plates in the 9 and 15 MeV Varian CL2300C/D electron beams.
Figure 4.11 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for aluminum backscatter plates in the 6, 12, and 18 MeV Varian CL2300C/D electron beams.

Figure 4.12 Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for aluminum backscatter plates in the 9 and 15 MeV Varian CL2300C/D electron beams.
4.2 Validation of the NACP-02 Monte Carlo model

**Figure 4.13** Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for copper backscatter plates in the 6, 12, and 18 MeV Varian CL2300C/D electron beams.

**Figure 4.14** Measured and MC calculated backscatter factors for the NACP-02 ionization chamber for copper backscatter plates in the 9 and 15 MeV Varian CL2300C/D electron beams.
While increasing the front window’s graphite thickness by 40% may seem too dramatic, a broken NACP-02 chamber became available for dissection at the end of this project. Although exact figures can not be given due to a confidentiality agreement with the chamber’s manufacturer, measurements performed by the NPL showed that the mylar foil was actually 70% thicker than specified. As for the graphite front window, the manufacturer’s specification for its thickness was correct. However, the front window’s graphite density was revealed to be about 30% denser than the graphite in the backing of the chamber. In the simulations, the graphite in the chamber’s front window and back wall was assumed to have a density of 1.8 g/cm$^3$. Measurements by the NPL found the front window graphite closer to 2.25 g/cm$^3$ and the graphite back closer to 1.74 g/cm$^3$. It turns out then that the tuned NACP-02 chamber model and the sacrificed NACP-02 chamber have approximately the same front window mass thickness of 140 mg/cm$^2$. This number is different from the 104 mg/cm$^2$ listed in the IAEA’s TRS-398 absorbed dose protocol. All other differences between the tuned chamber model and the sacrificed chamber were considered minor for the electron beam energies 6 – 18 MeV.

The differences between the sacrificed chamber and the Monte Carlo chamber model, however, were probably significant for the 4 MeV beam as agreement between the measured and simulated BSF values was difficult to achieve. The 4 MeV BSF simulations were highly sensitive to chamber model and positioning due to the fact that attenuation of the low energy beam by the chamber caused BSF measurements to be made in the water equivalent PDD tail region of 70-30% . To illustrate the point, before tuning the chamber model, the simulated 4 MeV BSF values for copper were 3% greater than the measured BSF values but after tuning the chamber model, the copper MC BSF values were up to 4.5% less than the measured BSF values. This amounts to a difference of 7.5% for the 4 MeV beam whereas the 6 – 18 MeV beams only experienced a 1–2% change in copper MC BSF results due to tuning of the chamber model.
Despite the difficulties with the 4 MeV BSF results, the excellent BSF results achieved for the 6 – 18 MeV CL2300C/D beams lead us to believe the tuned Monte Carlo NACP-02 chamber model was sufficiently accurate for our perturbation factor calculations.

### 4.3 Mean Spencer-Attix mass restricted collisional stopping power ratios

Figures 4.15 and 4.16 show the SPRRZnrc MC simulated mean Spencer-Attix mass restricted collisional stopping powers ratios water-to-air, $s_{w,air}$, for the Varian clinical (4-18 MeV) and the NPL (4–19 MeV) electron beams at $z_{ref}$, $z_{max}$, and $R_{50}$. The $s_{w,air}$ values calculated using the Burns equations (eq. 1.10 and 1.11) are also indicated with dotted lines. For the Varian clinical electron beams, the difference between the SPRRZnrc and the Burns calculated $s_{w,air}$ at $z_{ref}$ ranged from 0.0% (9 MeV) to 0.4% (18 MeV). At $R_{50}$, the differences in $s_{w,air}$ ranged from 0.0% (18 MeV) to 0.4% (6 MeV). In the case of the NPL electron beams, $s_{w,air}$ differences were from 0.0% (12 MeV) to 0.4% (19 MeV) at $z_{ref}$ and 0.5% (6 MeV) to 0.7% (19 MeV) at $R_{50}$.

![Figure 4.15](image.png)

**Figure 4.15** Spencer-Attix mass stopping-power ratios water-to-air ($\Delta = 10$ keV) on the central axis in water at depths, $z_{max}$, $z_{ref}$ and $R_{50}$ for the Varian electron beams.
Figure 4.16 Spencer-Attix mass stopping-power ratios water-to-air ($\Delta = 10$ keV) on the central axis in water at depths, $z_{max}$, $z_{ref}$ and $R_{50}$ for the NPL electron beams.

Figures 4.17 and 4.18 show the SPRRZnrc MC simulated Spencer-Attix mass restricted collisional stopping powers ratios graphite-to-air, $s_{g, air}$, for the Varian clinical (4 - 18 MeV) and the NPL (4 – 19 MeV) electron beams at depths between $z_{ref}$ and $R_{50}$. 
Figure 4.17 Spencer-Attix mass stopping-power ratios graphite-to-air ($\Delta = 10$ keV) on the central axis in graphite at depths, $z_{max}$, $z_{ref}$ and $R_{50}$ for the Varian electron beams.

Figure 4.18 Spencer-Attix mass stopping-power ratios graphite-to-air ($\Delta = 10$ keV) on the central axis in graphite at depths, $z_{max}$, $z_{ref}$ and $R_{50}$ for the NPL electron beams.
4.4 Electron perturbation correction factors for the NACP-02 plane-parallel ionization chamber

4.4.1 Perturbation factor results calculated in water

DOSRZnrc calculated perturbation correction factors in water for the NACP-02 plane-parallel ionization chamber at reference depth, \( z_{ref} \), for the Varian electron beams are shown in figure 4.19 with respect to the beam quality specifier, \( R_{50} \). The error bars indicate uncertainties of one standard deviation. With values ranging from 0.998 ± 0.2% to 1.004 ± 0.3%, \( p_{cav} \) in general was approximately unity. Therefore, the main influence on the overall perturbation correction factor, \( p_Q \), was \( p_{wall} \) which ranged from 1.008 ± 0.3% at the highest energy of 18 MeV to 1.017 ± 0.3% at the lowest energy of 4 MeV. As expected, the lower energy electron beams experienced the highest overall chamber perturbation in dose deposited in the scoring volume due to their larger interaction probabilities and scattering powers with the chamber materials. \( p_Q \) was 2.0% and 1.3% above unity for the 4 MeV CL21EX and the 6 MeV CL2300C/D electron beams while for electron energies 9 MeV and greater, \( p_Q \) was between 0.8% to 0.9% above unity.
Figure 4.19 Calculated perturbation factors $p_{cav}$, $p_{wall}$ and $p_Q$ in water for the NACP-02 ionization chamber at reference depth, $z_{ref}$, in the Varian linac beams as a function of beam quality specifier, $R_{50}$.

Figures 4.20 – 4.22 compare this work’s results for $p_{cav}$, $p_{wall}$ and $p_Q$ in water at $z_{ref}$ for the NACP-02 chamber to results obtained by Zakikhani (2006), Buckley and Rogers (2006), and to results calculated for a chamber model based on measurements of a sacrificed chamber. This was to test the reproducibility of the results as well as to determine whether tuning the chamber model against backscatter factors was an important step in the Monte Carlo model validation process. Buckley and Rogers performed no tuning of their chamber model, while Zakikhani’s tuning of his model was not as comprehensive or successful as that performed in this work. The error bars indicate uncertainties of one standard deviation.

In figure 4.20, $p_{cav}$ values calculated for this work with the tuned chamber model are compared against results calculated by Zakikhani (2006) and against results calculated using the sacrificed chamber model. No significant differences were expected for the $p_{cav}$ values as the dimensions of the air cavity used in the simulations were very similar. The $p_{cav}$ value for this work and that of the sacrificed
chamber model for the 6 MeV beam were nearly identical. However, there was a notable difference between the results of this work and Zakikhani’s work. This work’s $p_{cav}$ values were larger than Zakikhani’s by 0.5% for the 6 MeV beam and up to 0.7% greater for the 18 MeV beam. This difference is most likely due to the fact that Zakikhani used an ECUT of 521 keV in both his DOSRZnrc dose calculations and his SPRRZnrc stopping power calculations while the calculations for this work used an ECUT of 512 keV in the DOSRZnrc dose scoring region and immediate surrounding regions while the SPRRZnrc stopping power calculations used an ECUT of 521 keV. The selection of 512 keV for DOSRZnrc in this work was made to achieve the greatest accuracy in electron transport within the chamber. The selection of 521 keV for SPRRZnrc was made in order to be consistent with dosimetry protocols and to match the CSDA range to the 2.6 mm mean chord length of the NACP-02 chamber’s air cavity. Zakikhani’s results for $p_{cav}$ and $p_Q$ in the 6 MeV beam were reproducible once our ECUT values were set to 521 keV. Differences in chamber model do not affect the calculation of $p_{cav}$ values (eqn. 3.3).

![Figure 4.20](image_url)  
**Figure 4.20** Calculated perturbation factors $p_{cav}$ in water for the NACP-02 ionization chamber at reference depth, $z_{ref}$, in the Varian linac beams as a function of beam quality specifier, $R_{50}$.  

55
Figure 4.21 compares the values of $p_{wall}$ from this work to those calculated by Zakikhani (2006), Buckley and Rogers (2006), and those calculated for the sacrificed chamber model. The values calculated by Zakikhani in general were greater than the values of this work by up to 0.6%. Buckley and Rogers, using ECUT values of 521 keV, had values that were greater by up to 0.6%. Differences in results between this work and the latter two works are likely due to the lower ECUT values and the 35% increase in mass density of the chamber front window used in this work (section 4.2). There was no significant difference in the $p_{wall}$ value for the 6 MeV electron beam when the sacrificed chamber model was used. The sacrificed chamber model used the same combination of 512 and 521 keV ECUT values and chamber front window mass density as this work.

![Figure 4.21](image)

**Figure 4.21** Calculated perturbation factors $p_{wall}$ in water for the NACP-02 ionization chamber at reference depth, $z_{ref}$, in the Varian linac beams as a function of beam quality specifier, $R_{50}$.

In figure 4.22, the $p_Q$ values of Zakikhani are lower than the values of this work by up to 0.5% for the 6 MeV and 18 MeV electron beams. Zakikhani’s lower $p_Q$ values are due to his lower $p_{cav}$ values. Therefore, the main reason for the difference in results is the choice of ECUT values as explained previously. Using the
sacrificed chamber model rather than the backscatter tuned chamber model was not significant to the calculation results at \( z_{ref} \) for the 6 MeV beam. \( z_{ref} \) is the depth at which calibration and reference dosimetry are performed. A difference of 0.5\% in calculated \( p_Q \) values is significant for radiotherapy level primary standards.

\[\begin{align*}
\text{beam quality} & \quad R_{50} \\
\text{this work} & \quad \diamondsuit \\
\text{Zakikhani (2006)} & \quad \bigcirc \\
\text{sacrificed chamber} & \quad \bigcirc
\end{align*}\]

Figure 4.22 Calculated perturbation factors \( p_Q \) in water for the NACP-02 ionization chamber at reference depth, \( z_{ref} \), in the Varian linac beams as a function of beam quality specifier, \( R_{50} \).

Figures 4.23 to 4.25 show the increase in value of \( p_{cav} \), \( p_{wall} \) and \( p_Q \) in water with depth from \( z_{ref} \) to \( R_{50} \) for the NACP-02 chamber. Results obtained by Zakikhani et al (2006), Buckley and Rogers (2006), and those based on the sacrificed chamber model are also shown. At deeper depths in the water phantom, the difference between the values calculated in this work and other works increased. At \( R_{50} \), the largest difference in \( p_{cav} \), \( p_{wall} \) and \( p_Q \) values between this work and Zakikhani’s work was 1.1\% (15 MeV), 1.0\% (6 MeV) and 1.7\% (6 MeV) respectively. The difference in \( p_{wall} \) values for the 6 MeV beam between this work and Buckley and Rogers’ work increased to 2.8\% at \( R_{50} \). The increased discrepancies between this work and the works of Zakikhani and Buckley and Rogers are due to the previously mentioned differences in ECUT values and chamber parameters that are amplified in the high
gradient region of the PDD curve. Specifically, the significantly thicker front window of the tuned chamber model of this work will greatly affect the $p_{wall}$ and $p_Q$ results at phantom depths were no charge particle equilibrium exists. Even the tuned chamber model, which was sufficiently accurate to calculate similar perturbation factors as the sacrificed chamber model at $z_{refs}$, became inadequate at deeper depths. For the 6 MeV beam, the difference between the tuned chamber model and the sacrificed chamber model at $R_{50}$ was 1.4% for $p_{wall}$ and 1.3% for $p_Q$.

![Graph showing calculated perturbation factors $p_{cav}$ in water for the NACP-02 ionization chamber at reference depth, $z_{refs}$, and $R_{50}$ in the Varian linac beams.](image)

**Figure 4.23** Calculated perturbation factors $p_{cav}$ in water for the NACP-02 ionization chamber at reference depth, $z_{refs}$, and $R_{50}$ in the Varian linac beams.
Figure 4.24 Calculated perturbation factors $p_{\text{wall}}$ in water for the NACP-02 ionization chamber at reference depth, $z_{\text{ref}}$, and $R_{50}$ in the Varian linac beams.

Figure 4.25 Calculated perturbation factors $p_Q$ in water for the NACP-02 ionization chamber at reference depth, $z_{\text{ref}}$, and $R_{50}$ in the Varian linac beams.
4.4.2 Perturbation factor results calculated in graphite

DOSRZnrc calculated perturbation correction factors in graphite for the NACP-02 plane-parallel ionization chamber at reference depth, $z_{ref}$, with respect to the beam quality specifier, $R_{50}$, are shown in figure 4.26 for the Varian electron beams and figure 4.27 for the NPL electron beams. The error bars indicate uncertainties of one standard deviation. For the Varian beams, the cavity perturbation factor, $p_{cav}$, exhibited a small increasing trend with energy. The $p_{cav}$ values of the Varian linacs ranged from $0.994 \pm 0.2\%$ for the 4 MeV beam to $1.000 \pm 0.1\%$ for the 18 MeV beam. There was no clear energy dependence for the $p_{cav}$ values of the NPL linac electron beams. $p_{cav}$ for the NPL linac beams fluctuated between 0.6% and 1.0% below unity for beam energies less than 12 MeV before increasing to 0.4% and 0.3% below unity for the 16 and 19 MeV beams.

A decrease in wall perturbation factor, $p_{wall}$, with increasing beam energy was seen for both the Varian and NPL linacs. The perturbation caused by the chamber walls was largest for the 4 MeV CL21EX beam with a $p_{wall}$ value of $1.022 \pm 0.2\%$ and for the 6 MeV NPL beam with a $p_{wall}$ value of $1.017 \pm 0.2\%$. The combined perturbations caused by the chamber cavity and chamber walls resulted in the overall perturbation factor, $p_{Q}$, for all linac energies except the 12 MeV NPL beam being significantly larger than unity. The largest $p_{Q}$ value was 1.5% above unity for the 4 MeV CL21EX linac and 1.1% above unity for the 6 MeV NPL linac.
Figure 4.26 Calculated perturbation factors $p_{\text{cav}}$, $p_{\text{wall}}$ and $p_Q$ in graphite for the NACP-02 ionization chamber at reference depth, $z_{\text{ref}}$, in the Varian linac beams as a function of beam quality specifier, $R_{50}$.

Figure 4.27 Calculated perturbation factors $p_{\text{cav}}$, $p_{\text{wall}}$ and $p_Q$ in graphite for the NACP-02 ionization chamber at reference depth, $z_{\text{ref}}$, in the NPL linac beams as a function of beam quality specifier, $R_{50}$. 
Figures 4.28 – 4.30 display the values of the Varian linac perturbation factors $p_{cav}$, $p_{wall}$, and $p_Q$ in graphite for the NACP-02 ionization chamber at depths between $z_{ref}$ and $R_{50}$. $p_{cav}$ increased with depth while $p_{wall}$ decreased with depth. Overall, the combination of $p_{cav}$ and $p_{wall}$ resulted in $p_Q$ increasing with depth. As expected the largest variation in perturbation factors with depth occurred for the lowest energy.

Figure 4.28 Calculated perturbation factors $p_{cav}$ in graphite for the NACP-02 ionization chamber at depths between $z_{ref}$ and $R_{50}$ in the Varian linac beams.
Figure 4.29 Calculated perturbation factors $p_{wall}$ in graphite for the NACP-02 ionization chamber at depths between $z_{ref}$ and $R_{50}$ in the Varian linac beams.

Figure 4.30 Calculated perturbation factors $p_Q$ in graphite for the NACP-02 ionization chamber at depths between $z_{ref}$ and $R_{50}$ in the Varian linac beams.
4.4.3 Perturbation factor ratios in the NPL calibration process

The NPL calibration process (section 1.2) requires knowledge of their NACP-02 reference chamber’s ratio of $p_Q$ in water over $p_Q$ in graphite, $p_{\text{ref,w}}/p_{\text{ref,g}}$, at $z_{\text{ref}}$. Using the NPL $p_Q$ results in water calculated by Zakikhani (2006) and the NPL $p_Q$ results in graphite calculated in this work (figure 4.27), the ratio $p_{\text{ref,w}}/p_{\text{ref,g}}$ is calculated and shown in table 4.5 and figure 4.31. Only the 4 and 12 MeV beams are significantly different from unity by 0.8% and 0.7% respectively. Results calculated in 1998 by Williams et al using the less accurate EGS4 code are also shown.

<table>
<thead>
<tr>
<th>Nominal Energy (MeV)</th>
<th>This Work</th>
<th>Williams et al (1998)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_{\text{ref,w}}/p_{\text{ref,g}}$</td>
<td>SDOM (±%)</td>
</tr>
<tr>
<td>4</td>
<td>1.008</td>
<td>0.3%</td>
</tr>
<tr>
<td>6</td>
<td>0.998</td>
<td>0.3%</td>
</tr>
<tr>
<td>8</td>
<td>1.003</td>
<td>0.3%</td>
</tr>
<tr>
<td>10</td>
<td>0.998</td>
<td>0.3%</td>
</tr>
<tr>
<td>12</td>
<td>1.007</td>
<td>0.3%</td>
</tr>
<tr>
<td>16</td>
<td>1.001</td>
<td>0.3%</td>
</tr>
<tr>
<td>19</td>
<td>0.999</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

Table 4.5 The ratio of overall perturbation factors $p_Q$ in water over $p_Q$ in graphite ($p_{\text{ref,w}}/p_{\text{ref,g}}$) for the NACP-02 chamber at $z_{\text{ref}}$ in the NPL linac electron beams 4 – 19 MeV.
4.4.4 Scaling the NACP-02 front chamber window for the phantom material’s equivalent thickness

From the calculations performed in section 4.4.1 and 4.4.2, it was shown that \( p_{\text{wall}} \) increased with depth in water (figure 4.24) and decreased with depth in graphite (figure 4.29). Before investigating the reasons behind the observed trends, a closer look into the calculations of \( p_{\text{wall}} \) is required. As explained in section 3.4 of the Materials and Methods chapter, \( p_{\text{wall}} \) is defined as the ratio of dose in case b to the dose in case c (figure 3.6) where the effective point of measurement is the inside centre of the front chamber window and where no scaling of the front chamber window for its water equivalent or graphite equivalent thickness, depending on the phantom material, is performed. Whether scaling is performed in the graphite phantom is not important as the NACP-02’s front window is mainly composed of graphite, albeit of a different density, and would result in a positioning error of only...
0.001 cm for the tuned chamber model. However, whether scaling is performed in a water phantom is of much greater importance as the difference in densities between water and the materials of the front chamber window is much larger and would result in a positioning error of 0.060 cm.

There is some non-uniformity in the protocols on whether scaling should or should not be performed. In TG-51, it is only mentioned that the inside centre of the chamber’s front window should be positioned at $z_{ref}$, where $z_{ref}$ is specified in cm. On the other hand, both the IPEM code of practice (Thwaites et al 2003) and the TRS-381 (Andreò et al 1997) explicitly state that the front chamber wall should be converted to a phantom equivalent thickness. TRS-398 (Andreò et al 2000) follows the procedure given in TRS-381 and gives $z_{ref}$ in g/cm$^2$ and the front chamber window thickness in mg/cm$^2$ which suggests that scaling should be performed.

Figure 4.32 shows the values of $p_{wall}$ at $z_{ref}$ in water for the situation where scaling of the front chamber window has and has not been performed. There is no significant difference in the results and hence the overall perturbation factor, $p_Q$, is also not affected (figure 4.33).
Figure 4.32 Comparing the effect of scaling the NACP-02 front chamber window on $p_{wall}$ values in water at depth $z_{ref}$ in the Varian linac beams.

Figure 4.33 Comparing the effect of scaling the NACP-02 front chamber window on $p_Q$ values in water at depth $z_{ref}$ in the Varian linac beams.
However as the measurement depth moves deeper, not scaling for the front chamber window can greatly alter the results because a positioning difference of 0.060 cm in the high gradient tail of a water PDD curve would not only lead to a dose difference of several percentage points but also a difference in the multiple scattering of the charged particles due to a different energy spectrum. Figures 4.34 and 4.35 compare the results of $p_{wall}$ and $p_Q$ respectively at $R_{50}$ in water when scaling has and has not been performed. For the $p_{wall}$ results (figure 4.34), the largest difference in values between the unscaled and scaled results was 20% for the 4 MeV beam and 12% for the 6 MeV beam. The smallest difference was 4.5% for the 18 MeV beam. Similarly for the $p_Q$ results (figure 4.35), the largest difference was 21.3% for the 4 MeV while the 18 MeV had the smallest difference of 4.5%.

**Figure 4.34** Comparing the effect of scaling the NACP-02 front chamber window on $p_{wall}$ values in water at depth $R_{50}$ in the Varian linac beams.
Figure 4.35 Comparing the effect of scaling the NACP-02 front chamber window on $p_Q$ values in water at depth $R_{50}$ in the Varian linac beams.

Clearly not scaling the chamber front window can lead to a steep increase in perturbation factor values with depths between $z_{ref}$ and $R_{50}$ on the order of 3% to 14% for $p_{wall}$ and 4% to 21% for $p_Q$ (figures 4.24 and 4.25). However, if scaling is performed on the front window, the change in the values of $p_{wall}$ with depth is much smaller from -0.8% to -6% (figure 4.36). Change in $p_Q$ values are also minimized. Between $z_{ref}$ and $R_{50}$, there is no significant difference in the $p_Q$ values for the 4, 6, 9, and 18 MeV beams while the 12 and 15 MeV beams have a small increase of only 0.7% and 0.8% (figure 4.37).
Figure 4.36 Calculated perturbation factor $p_{wall}$ for the NACP-02 chamber in water at depths $z_{ref}$ and $R_{50}$ in the Varian linac beams where scaling for the front chamber window has been performed.

Figure 4.37 Calculated perturbation factor $p_Q$ for the NACP-02 chamber at depths $z_{ref}$ and $R_{50}$ in the Varian linac beams where scaling for the front chamber window has been performed.
While the large discrepancies in the values of $p_{\text{wall}}$ and $p_Q$ at depths deeper than $z_{\text{ref}}$ caused by scaling or not scaling the front chamber window for the phantom equivalent thickness is academically interesting, it is not particularly relevant for clinical purposes. If no scaling for the front window is performed and the resulting $p_Q$ values are used to correct the PDD curves, the clinically relevant beam quality specifier, $R_{50}$, is shifted downstream by approximately 0.05 cm in water and 0.01 cm in graphite for the 6-18 MeV Varian linac electron beams. If scaling is performed for the $p_Q$ calculations, there is no discernible difference in $R_{50}$ values between uncorrected and corrected PDD curves.

Finally, it was hypothesized that the perturbation caused by the chamber walls, $p_{\text{wall}}$, would be less in the graphite phantom than in the water phantom as the NACP-02 chamber is composed largely of graphite. This was shown to be false in figure 4.38. Near $z_{\text{ref}}$, $p_{\text{wall}}$ values in water were closer to unity than those in graphite once scaling for the water equivalent thickness of the front chamber window was taken into account. As the $p_{\text{wall}}$ and $p_{\text{cav}}$ values at $R_{50}$ in graphite are both greater than those in water (figure 4.38 and 4.39), it is no surprise then that the overall perturbation values, $p_Q$, at $R_{50}$ in graphite are also larger than in water (figure 4.40).
Figure 4.38 Comparing the NACP-02 chamber values of $p_{\text{wall}}$ in water (with front window scaled) to those in graphite for depths $z_{\text{ref}}$ and $R_{50}$ in the Varian linac beams a) 4, 9, and 15 MeV and b) 6, 12, and 18 MeV.

Figure 4.39 Comparing the NACP-02 chamber values of $p_{\text{cav}}$ in water (with front window scaled) to those in graphite for depths $z_{\text{ref}}$ and $R_{50}$ in the Varian linac beams a) 4, 9, and 15 MeV and b) 6, 12, and 18 MeV.
Verhaegen et al. (2006) hypothesized that the change in perturbation factors with depth was somehow due to the wider angular distribution and lower mean electron energy at greater depths in the phantoms that would create more backscatter from the chamber back wall. While it is true that the mean electron energy is lower (table 4.6) and that the angular distribution is wider (table 4.7) at deeper depths, more backscatter is not created (figure 4.41b). In the tables 4.6 and 4.7, first time crossers and multi-crossers refer to the number of times the electrons have passed through the phase space scoring plane located just behind the air cavity. As the percentage of electrons that pass through the scoring plane more than twice is minute, multi-crossers will be considered approximately equivalent to particles moving in the backward direction (> 90 degrees).
### 4.4.5 Hypothesis explaining the decrease in $p_{wall}$ with depth in water

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Case</th>
<th>Depth</th>
<th>Mean energy of first time crossers (MeV)</th>
<th>Mean energy of multi-crossers (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>B</td>
<td>$z_{ref}$</td>
<td>2.84</td>
<td>0.84</td>
</tr>
<tr>
<td>6</td>
<td>C scaled</td>
<td>$z_{ref}$</td>
<td>2.88</td>
<td>0.85</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>$R_{50}$</td>
<td>1.20</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>C scaled</td>
<td>$R_{50}$</td>
<td>1.22</td>
<td>0.49</td>
</tr>
<tr>
<td>18</td>
<td>B</td>
<td>$z_{ref}$</td>
<td>6.78</td>
<td>1.00</td>
</tr>
<tr>
<td>18</td>
<td>C scaled</td>
<td>$z_{ref}$</td>
<td>6.81</td>
<td>0.96</td>
</tr>
<tr>
<td>18</td>
<td>B</td>
<td>$R_{50}$</td>
<td>2.55</td>
<td>0.78</td>
</tr>
<tr>
<td>18</td>
<td>C scaled</td>
<td>$R_{50}$</td>
<td>2.56</td>
<td>0.76</td>
</tr>
</tbody>
</table>

**Table 4.6** Mean electron energy of particles in phase space file collected just behind the air cavity for both case b and case c in water phantom.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Case</th>
<th>Depth</th>
<th>Mean angle of first time crossers</th>
<th>Mean angle of multi-crossers</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>B</td>
<td>$z_{ref}$</td>
<td>31.48</td>
<td>120.75</td>
</tr>
<tr>
<td>6</td>
<td>C scaled</td>
<td>$z_{ref}$</td>
<td>31.17</td>
<td>120.59</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>$R_{50}$</td>
<td>36.46</td>
<td>121.17</td>
</tr>
<tr>
<td>6</td>
<td>C scaled</td>
<td>$R_{50}$</td>
<td>36.37</td>
<td>121.58</td>
</tr>
<tr>
<td>18</td>
<td>B</td>
<td>$z_{ref}$</td>
<td>26.14</td>
<td>120.13</td>
</tr>
<tr>
<td>18</td>
<td>C scaled</td>
<td>$z_{ref}$</td>
<td>25.94</td>
<td>120.28</td>
</tr>
<tr>
<td>18</td>
<td>B</td>
<td>$R_{50}$</td>
<td>34.31</td>
<td>120.41</td>
</tr>
<tr>
<td>18</td>
<td>C scaled</td>
<td>$R_{50}$</td>
<td>34.10</td>
<td>120.15</td>
</tr>
</tbody>
</table>

**Table 4.7** Mean angle of electrons in phase space file collected just behind the air cavity for both case b and case c in water.
Figure 4.41 Comparing angular distributions of the a) forward and b) backscattered electrons of case c behind the air cavity at \( z_{\text{ref}} \) and \( R_{50} \) for the 6 MeV CL2300C/D Varian beam in the water phantom.

The value of \( p_{\text{wall}} \) depends only on the ratio of doses in case b relative to case c (eq. 3.4). Therefore, what is relevant to examine is in what way case b differs significantly relative to case c such that significant differences in doses to the air cavity are also created. There is no notable difference in mean electron energy (table 4.6) or mean angular distribution (table 4.7). For the 6 and 18 MeV CL2300C/D beams, the shapes of the energy spectrum (figures 4.42 and 4.43) and angular distribution curves (figures 4.44 and 4.45) for case b and c are also similar. The only important difference between case b and case c’s energy spectrum and angular distribution curves is in the number of electrons that reached the air cavity. It is concluded then that dose differences between case b and case c are due mainly to the number of electron reaching the air cavity rather than a significant difference in the electron fluence’s angular distribution or energy spectrum.
4.4.5 Hypothesis explaining the decrease in $p_{wall}$ with depth in water

**Figure 4.42** Comparison of the energy spectrum of case b and case c for the 6 MeV CL2300C/D electrons immediately behind the air cavity in a water phantom. a) at $z_{ref}$ b) at $R_{50}$

**Figure 4.43** Comparison of the energy spectrum of case b and case c for the 18 MeV CL2300C/D electrons immediately behind the air cavity in a water phantom. a) at $z_{ref}$ b) at $R_{50}$
Chapter 4  4.4.5 Hypothesis explaining the decrease in $p_{wall}$ with depth in water

Figure 4.44 Comparison of the angular distributions of case b and case c for the 6 MeV CL2300C/D electrons immediately behind the air cavity in a water phantom. a) at $z_{ref}$ from 0-90°  b) at $z_{ref}$ from 90-180° c) at $R_{50}$ from 0-90° d) at $R_{50}$ from 90-180°
Figure 4.45 Comparison of the angular distributions of case b and case c for the 18 MeV CL2300C/D electrons immediately behind the air cavity in a water phantom. a) at $z_{\text{ref}}$ from 0–90° b) at $z_{\text{ref}}$ from 90-180° c) at $R_{50}$ from 0-90° d) at $R_{50}$ from 90-180°

The differences in particles reaching the air cavity are examined in more detail in table 4.8. The ratio of total case b over case c electrons reaching the air cavity is calculated along with data on the ratio of electrons moving in the forward direction (electrons < 90°) and the backward direction (electrons > 90°). As a rough generalization, forward electrons comprise about 90% of total electrons while
backscattered electrons are approximately 10%. Notice that the ratio of total electrons (table 4.8 column 1) is close to the actual value of $p_{wall}$. Obviously the two numbers are not exactly the same as dose deposition also depends on whether the electron is a high energy forward moving electron or a low energy backscattered electron.

<table>
<thead>
<tr>
<th>6MeV</th>
<th>18MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ratio of total # electrons</strong></td>
<td><strong>Ratio of electrons &lt;90° (forward)</strong></td>
</tr>
<tr>
<td>$z_{ref}$</td>
<td>1.0001</td>
</tr>
<tr>
<td>$R_{50}$</td>
<td>0.9659</td>
</tr>
<tr>
<td>$z_{ref}$</td>
<td>1.0017</td>
</tr>
<tr>
<td>$R_{50}$</td>
<td>0.9953</td>
</tr>
</tbody>
</table>

**Table 4.8** Comparison of the number of electrons in case b and case c reaching the back of the air cavity in water.

In general, case c has more particles moving in the forward direction (table 4.8 column 2) while case b has more backscattered electrons (table 4.8 column 3). The difference in the number of forward moving electrons is affected mainly by the front chamber graphite window while the difference in the backscattered electrons is influenced by the chamber’s graphite backing. The stopping power and scattering power of the chamber graphite are respectively 57-60% and 49-55% greater than water for the energy range of 0.01 – 20 MeV. Therefore due to the higher stopping power, both the front graphite window and the graphite back wall generate an increased shower of secondary electrons. We make the hypothesis that as the front graphite window is thin (0.07 cm) and electrons moving in the forward direction (<90°) have high energy (table 4.6 first time crossers), it allows much of the secondary electrons generated in the water above the chamber and within the graphite chamber window to reach the air cavity. Hence case c has more particles reaching the air cavity and the ratio of electrons < 90° is below unity (table 4.8 column 2).
For the chamber backing on the other hand, it is thick (0.74 cm) and backscattered electrons (> 90°) have low energy (table 4.6 multi-crossers). The graphite backing will generate greater secondary electron fluence relative to the water phantom. However, we speculate that due to the combination of the chamber graphite backing’s large thickness and higher scattering power, as well the low energy of the backscattered fluence, the overall effect is that the graphite backing (case c) has less particles relative to the water phantom backing (case b) reaching the air cavity and the ratio of electrons > 90° is above unity (table 4.8 column 3).

Differences in electron numbers between case b and case c reaching the air cavity translate to differences in dose deposited between case b and case c. Table 4.9 shows the percent difference in dose deposited between case b and case c separated into particles that reached the scoring air volume through the front window and back wall for the 6 and 18 MeV Varian electron beams. As hypothesized in the previous two paragraphs, the front chamber graphite window in case c increased the number of electrons entering the air cavity, thus the percent difference in dose contribution from the front wall between case b and c is negative (table 4.9 column 1). The back water wall in case b, except for the 6 MeV beam at $R_{50}$, contributed more electrons to the air cavity, thus the percent difference in dose contribution from the back wall between case b and case c is positive (table 4.9 column 2).

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>depth</th>
<th>% difference in dose = $(D_b - D_c)/D_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Contribution from front wall</td>
<td>Contribution from back wall</td>
</tr>
<tr>
<td>6 MeV</td>
<td>$z_{ref}$</td>
<td>-0.19%</td>
</tr>
<tr>
<td></td>
<td>$R_{50}$</td>
<td>-3.79%</td>
</tr>
<tr>
<td>18 MeV</td>
<td>$z_{ref}$</td>
<td>-0.31%</td>
</tr>
<tr>
<td></td>
<td>$R_{50}$</td>
<td>-1.62%</td>
</tr>
</tbody>
</table>

Table 4.9 Percent difference between case b and case c in dose contributions to the air cavity from the front wall and the back wall for the 6 and 18 MeV Varian electron beams at $z_{ref}$ and $R_{50}$ in a water phantom.
Chapter 4

4.4.5 Hypothesis explaining the decrease in $p_{wall}$ with depth in water

As the NACP-02 chamber’s front graphite window and back graphite wall have opposing effects on the number of particles reaching the air cavity, the final $p_{wall}$ value in water is a balance between the influences of these two walls. The front chamber’s graphite window increases dose to the air cavity while the back graphite wall decreases dose to the air cavity. Because $p_{wall}$ is greater than unity at $z_{ref}$ (table 4.8), it appears the back graphite wall effects dominate at this depth. At deeper depths, the mean electron energy is lower making the electron ranges shorter. We hypothesize that while shorter electron ranges can magnify the effect of the graphite front window on the number of forward particles reaching the air cavity due to the high mean energy of the electrons and the thinness of the window, it also minimizes the effect of the thick graphite back wall as many backscattered electrons have such low energies that ranges in both cases b and c that are too short to reach the air cavity. This is evident from table 4.8 where at $R_{50}$, the ratio of electrons $< 90^\circ$ (column 2) moves even further away from unity while the ratio of electrons $> 90^\circ$ (column 3) moves closer to unity. As well in table 4.9, the difference in the front wall dose contribution between case b and case c increases at $R_{50}$ (column 1) while the difference in the back wall contribution decreases (column 2). Therefore at deeper depths in the water phantom, $p_{wall}$ decreases due to the increasing importance of the graphite front window (case c) in scattering more particles into the air cavity and hence depositing more dose than case b.

The above analysis of $p_{wall}$ in water is simplified because it ignores the effects caused by the chamber’s rexolite side walls. Although rexolite side walls also cause electron fluence perturbation, ignoring it in the analysis was considered acceptable as the effects of the graphite chamber walls dominated any effects caused by rexolite, whose properties are closer to water. An analysis of $p_{wall}$ in the graphite phantom was attempted but in this case the effects of the rexolite in the chamber could not be ignored leading to a more complicated analysis. No coherent hypothesis was formulated.
4.4.6 The effects of the NACP-02’s side, back, and front chamber walls on the value of $p_{wall}$ in water and graphite phantoms

Tables 4.10 and 4.11 display the effects on $p_{wall}$ in water when the back, side, or front of the NACP-02 chamber is replaced with water. Calculations are for the 6 and 18 MeV CL2300C/D Varian linac at depths $z_{ref}$ and $R_{50}$. Data in table 4.10 was calculated without scaling the front chamber window for its water equivalent thickness while scaling was performed for the calculations in table 4.11. In both tables and for both energies, the back and side walls have the greatest impact on the value of $p_{wall}$ at $z_{ref}$. The importance of the back wall at $z_{ref}$ is consistent with the hypothesis in the previous section. Our 6 MeV back wall result at $z_{ref}$ (table 4.10) is also consistent with the result achieved by Verhaegen et al (2006) who found that $p_{wall}$ decreased from 1.014 to 1.007 when the chamber back wall was set to water. In our case $p_{wall}$ decreased from 1.0145 to 1.0059.

At $R_{50}$, it is the front wall that has the most influence (tables 4.10 and 4.11). However, this is due only to the shift in the water equivalent depth of the effective point of measurement (EPOM) in a high gradient region of the PDD curve when the front graphite window is replaced with water. A better simulation to determine the effect of the front graphite window on the $p_{wall}$ value would be to simulate only the front graphite window with the side and back walls replaced with water. This setup would avoid shifting the water equivalent depth of the EPOM.
Table 4.10 Effect on $p_{wall}$ when the back, side, or front wall of the NACP-02 chamber is replaced with water at depths $z_{ref}$ and $R_{50}$ for the 6 and 18 MeV CL2300C/D beams. Case c is not scaled for the water equivalent thickness of the front chamber window.

<table>
<thead>
<tr>
<th>Energy</th>
<th>chamber part replaced with phantom material</th>
<th>depth</th>
<th>partial chamber $p_{wall}$</th>
<th>full chamber $p_{wall}$</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>back wall</td>
<td>$z_{ref}$</td>
<td>1.0059</td>
<td>1.0145</td>
<td>-0.85%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$z_{ref}$</td>
<td>1.0071</td>
<td></td>
<td>-0.73%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$z_{ref}$</td>
<td>1.0117</td>
<td></td>
<td>-0.28%</td>
</tr>
<tr>
<td></td>
<td>back wall</td>
<td>$R_{50}$</td>
<td>1.0846</td>
<td>1.0930</td>
<td>-0.76%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$R_{50}$</td>
<td>1.0698</td>
<td></td>
<td>-2.12%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$R_{50}$</td>
<td>1.0238</td>
<td></td>
<td>-6.33%</td>
</tr>
</tbody>
</table>

Table 4.11 Effect on $p_{wall}$ when the back, side, or front wall of the NACP-02 chamber is replaced with water at depths $z_{ref}$ and $R_{50}$ for the 6 and 18 MeV CL2300C/D beams. Case c is scaled for the water equivalent thickness of the front chamber window.

<table>
<thead>
<tr>
<th>Energy</th>
<th>chamber part replaced with phantom material</th>
<th>depth</th>
<th>partial chamber $p_{wall}$</th>
<th>full chamber $p_{wall}$</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>back wall</td>
<td>$z_{ref}$</td>
<td>1.0047</td>
<td>1.0118</td>
<td>-0.70%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$z_{ref}$</td>
<td>1.0064</td>
<td></td>
<td>-0.53%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$z_{ref}$</td>
<td>1.0100</td>
<td></td>
<td>-0.18%</td>
</tr>
<tr>
<td></td>
<td>back wall</td>
<td>$R_{50}$</td>
<td>0.9674</td>
<td>0.9731</td>
<td>-0.59%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$R_{50}$</td>
<td>0.9603</td>
<td></td>
<td>-1.32%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$R_{50}$</td>
<td>0.9219</td>
<td></td>
<td>-5.26%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th>chamber part replaced with phantom material</th>
<th>depth</th>
<th>partial chamber $p_{wall}$</th>
<th>full chamber $p_{wall}$</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 MeV</td>
<td>back wall</td>
<td>$z_{ref}$</td>
<td>1.0010</td>
<td>1.0037</td>
<td>-0.27%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$z_{ref}$</td>
<td>1.0002</td>
<td></td>
<td>-0.35%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$z_{ref}$</td>
<td>1.0065</td>
<td></td>
<td>0.28%</td>
</tr>
<tr>
<td></td>
<td>back wall</td>
<td>$R_{50}$</td>
<td>0.9952</td>
<td>0.9956</td>
<td>-0.04%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$R_{50}$</td>
<td>0.9932</td>
<td></td>
<td>-0.24%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$R_{50}$</td>
<td>0.9800</td>
<td></td>
<td>-1.57%</td>
</tr>
</tbody>
</table>
Table 4.12 displays the effects on $p_{\text{wall}}$ in the graphite phantom when the back, side, or front of the NACP-02 chamber is replaced with the phantom material. Calculations are for the 6 and 18 MeV CL2300C/D Varian linac at depths $z_{\text{ref}}$ and $R_{50}$. For the 6 MeV, replacing the side chamber wall had the greatest impact at both $z_{\text{ref}}$ and $R_{50}$, while for the 18 MeV beam, it was the back wall. The difference is likely attributed to the wider angular distribution for the lower energy 6 MeV electron beam.

<table>
<thead>
<tr>
<th>Energy</th>
<th>chamber part replaced with phantom material</th>
<th>depth</th>
<th>partial chamber $p_{\text{wall}}$</th>
<th>full chamber $p_{\text{wall}}$</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>back wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0122</td>
<td>1.0158</td>
<td>-0.35%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0019</td>
<td></td>
<td>-1.37%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0161</td>
<td>1.0194</td>
<td>0.03%</td>
</tr>
<tr>
<td></td>
<td>back wall</td>
<td>$R_{50}$</td>
<td>0.9824</td>
<td>0.9880</td>
<td>-0.57%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$R_{50}$</td>
<td>1.0043</td>
<td></td>
<td>1.65%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$R_{50}$</td>
<td>0.9875</td>
<td></td>
<td>-0.05%</td>
</tr>
<tr>
<td>18 MeV</td>
<td>back wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0053</td>
<td>1.0102</td>
<td>-0.49%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0066</td>
<td></td>
<td>-0.36%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$z_{\text{ref}}$</td>
<td>1.0081</td>
<td></td>
<td>-0.21%</td>
</tr>
<tr>
<td></td>
<td>back wall</td>
<td>$R_{50}$</td>
<td>1.0022</td>
<td>1.0093</td>
<td>-0.70%</td>
</tr>
<tr>
<td></td>
<td>side wall</td>
<td>$R_{50}$</td>
<td>1.0071</td>
<td></td>
<td>-0.22%</td>
</tr>
<tr>
<td></td>
<td>front wall</td>
<td>$R_{50}$</td>
<td>1.0046</td>
<td></td>
<td>-0.47%</td>
</tr>
</tbody>
</table>

Table 4.12 Effect on $p_{\text{wall}}$ when the back, side, or front wall of the NACP-02 chamber is replaced with graphite at depths $z_{\text{ref}}$ and $R_{50}$ for the 6 and 18 MeV CL2300C/D beams.

4.4.7 Hypothesis explaining the increase in $p_{\text{cav}}$ value with depth in water and graphite phantoms

The $p_{\text{cav}}$ value is a balance between the opposing effects of obliquity that increase the value of $p_{\text{cav}}$ and the effects of in-scattering that decrease the value of $p_{\text{cav}}$. 

84
4.4.7 Hypothesis explaining the increase in $p_{cav}$ value with depth

in the chamber’s air cavity (case b). The obliquity effect is the loss of electron total path length within the air cavity because electrons scatter less than if the phantom material was present (figure 4.46b). The loss of path length means less dose is deposited within the air cavity and hence the $p_{cav}$ value must increase to compensate. In-scattering, on the other hand, is when more particles scatter into the cavity from the higher density phantom than those that scatter out due to the cavity being filled with low density air (figure 4.46a). In-scattering increases the dose deposited and hence the $p_{cav}$ value must decrease to compensate.

![Figure 4.46](image)

**Figure 4.46** Illustration of a) in-scattering and b) obliquity effect in electron beams.

Figure 4.47 shows $p_{cav}$ values calculated with the total electron fluence as well as $p_{cav}$ values calculated without the backscattered electron fluence created behind the air cavity for the 6 and 18 MeV CL2300C/D Varian electron beams in both water and graphite phantoms. We note that in the case where the total electron fluence is used, $p_{cav}$ in water increases from 0.9985 to 1.0415 for the 6 MeV beam and from 1.0011 to 1.0123 for the 18 MeV beam at depths $z_{ref}$ to $R_{50}$. However, when the backscattered electron fluence is eliminated and only electrons moving in the forward direction are considered, $p_{cav}$ in water decreases from 1.0342 to 0.9749 for the 6 MeV beam and
from 1.0704 to 1.0004 for the 18 MeV beam at depths $z_{ref}$ to $R_{50}$. Similar results were obtained for $p_{cav}$ in a graphite phantom.

**Figure 4.47** Comparing the $p_{cav}$ values calculated with total electron fluence vs. the $p_{cav}$ values calculated excluding backscattered electrons behind the air cavity at depths $z_{ref}$ and $R_{50}$ for the 6 and 18 MeV CL2300C/D electron beams in water and graphite phantoms.

We first consider only the forward electron fluence. At $z_{ref}$, the forward fluence $p_{cav}$ is greater than unity meaning the obliquity effect dominates. This is likely due to the higher mean electron energy at $z_{ref}$ than at $R_{50}$ (figure 4.48) that makes the particles more likely to leave the air cavity. At deeper depths, the in-scattering effect begins to dominate and forward fluence $p_{cav}$ decreases below unity. This is likely due to two factors. The first is a lower mean energy at deeper depths decreases the probability of a particle leaving the air cavity and hence minimizing the obliquity effect. The lower mean energy also increases the in-scattering effect due to an even greater difference in scattering power between the phantom material and the air cavity. The second factor is the angular distribution of electrons at deeper depths is wider than at $z_{ref}$ making in-scattering much more likely (figure 4.49). All these factors result in $p_{cav}$ decreasing with depth.
**Chapter 4**

**4.4.7 Hypothesis explaining the increase in $p_{cav}$ value with depth**

**Figure 4.48** Comparing forward fluence electron energy spectrums for 6 MeV beam case b at $z_{ref}$ vs. $R_{50}$ in a) water phantom b) graphite phantom (similar graphs were obtained for the 18 MeV beam).

**Figure 4.49** Comparing forward fluence electron angular distributions for 6 MeV beam case b at $z_{ref}$ vs. $R_{50}$ in a) water phantom b) graphite phantom (similar graphs were obtained for the 18 MeV beam).

While the forward electron fluence causes $p_{cav}$ to decrease with depth, the $p_{cav}$ value when the total fluence is considered, actually increases with depth (figure 4.47).
This means that despite the forward fluence electrons forming the majority of the particles entering the air cavity (figure 4.50), it is actually the minority backscattered electrons that most greatly affect the value of $p_{cav}$.

**Figure 4.50** Comparing the energy spectrums of the total, forward, and backward electron fluence for the 6 MeV beam case b a) $z_{ref}$ in water phantom b) $R_{50}$ in water phantom c) $z_{ref}$ in graphite phantom d) $R_{50}$ in graphite phantom (similar graphs were obtained for the 18 MeV beam).
Angular distribution of the backscattered electrons is not the cause for the increase in $p_{cav}$ value with depth as the distribution does not change significantly (figure 4.51). We speculate that the most likely cause is the decrease in the energy of the backscattered electrons with depth. The NACP-02 chamber was designed to have a $p_{cav}$ value near unity at $z_{ref}$ meaning the effects of obliquity and in-scattering are nearly equal. However at deeper depths, while in-scattering still occurs, the electrons’ lower mean energy and shorter range probably make the guard ring of the chamber more effective at blocking the in-scattered particles from reaching the scoring air volume. The guard ring is filled with air and table 4.13 shows that the electron CSDA range in air decreases by approximately 54% from $z_{ref}$ to $R_{50}$ for the 6 MeV beam in both water and graphite phantoms. The obliquity effect therefore dominates at deeper depths and $p_{cav}$ increases in value.

![Figure 4.51](image)

**Figure 4.51** Comparing the normalized angular distributions of the backscattered electrons at $z_{ref}$ to those at $R_{50}$ for a 6 MeV beam case b in a) water phantom and b) graphite phantom (similar graphs were obtained for the 18 MeV beam).
4.4.7 Hypothesis explaining the increase in $p_{\text{cav}}$ value with depth

<table>
<thead>
<tr>
<th>Energy</th>
<th>Depth</th>
<th>Mean energy of backscattered electrons (MeV)</th>
<th>CSDA energy (MeV)</th>
<th>CSDA in air (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6MeV water</td>
<td>$z_{\text{ref}}$</td>
<td>0.9215</td>
<td>0.90</td>
<td>0.4316</td>
</tr>
<tr>
<td></td>
<td>$R_{50}$</td>
<td>0.5177</td>
<td>0.50</td>
<td>0.1995</td>
</tr>
<tr>
<td></td>
<td>~% decrease in range</td>
<td></td>
<td></td>
<td>54%</td>
</tr>
</tbody>
</table>

| 6MeV graphite | $z_{\text{ref}}$ | 0.9050                                      | 0.90              | 0.4316              |
|              | $R_{50}$ | 0.5090                                      | 0.50              | 0.1995              |
|              | ~% decrease in range |                          |                   | 54%                 |

Table 4.13 Mean energy and approximate CSDA range of backscattered electrons in air for the 6 MeV beam at depths $z_{\text{ref}}$ and $R_{50}$ in water and graphite phantoms (similar analysis was performed for the 18 MeV beam).
Chapter 5 Conclusion

The Varian linacs CL2300C/D (6 – 18 MeV) and CL21EX (4 MeV) were modelled using the Monte Carlo EGSnrcMP user code BEAMnrcMP. An electron divergent point source was used in the simulations and primary electron energies were chosen such that the beam quality specifier, $R_{50}$, of the measured and simulated water PDD curves matched within 0.05 cm or less. Using the Varian linac models tuned in water and the NPL’s Radiation Dynamics Ltd. linac (4 - 19 MeV) previously tuned by Zakikhani (2006), PDD curves in a graphite phantom (1.77 g/cm$^3$) were simulated to obtain beam characteristics $R_{50}$, $z_{ref}$ and $z_{max}$. Phase space files were collected at a SSD of 100 cm for the Varian linacs and at a SSD of 200 cm for the NPL linac.

The NACP-02 plane-parallel ionization chamber was modeled using the EGSnrcMP user code CAVRZnrc. The initial Monte Carlo model was based on the specifications provided by Scanditronix but attempts to validate this model with measured backscatter factors (BSF) for copper, aluminum, graphite, and water failed. Simulated BSF values were larger than measured BSF values by 1-3%. After much experimentation, a final model was created that increased the chamber’s front window mass thickness by nearly 35% to 140 mg/cm$^2$. The new model produced agreement between the measured and calculated BSF values to within 1%, 0.5%, 0.36% and 0.36% for copper, aluminum, graphite and water, respectively for the energies 6 – 18 MeV. No agreement was achieved for the 4 MeV electron beam due to the high sensitivity to chamber model and positioning in the low energy beam.

The decision to increase the NACP-02 front window mass thickness by 35% was validated by measurements made on a broken NACP-02 chamber. The most surprising detail that emerged from the measurements was that the graphite density of the front chamber window at approximately 2.25 g/cm$^3$, is nearly 30% greater than the chamber’s graphite backing density. While the values for the graphite density and thickness of the front window of the tuned chamber model were not the same as the measured values, the
The resultant mass thickness of the front windows were equal. The mass thickness of 140 mg/cm² is much greater than the mass thickness of 104 mg/cm² listed in the IAEA’s TRS-398 absorbed dose protocol.

The EGSnrcMP user code SPRZnrc was used to calculate the Spencer-Attix mass restricted collisional stopping power ratios water-to-air, $s_{w, \text{air}}$, and graphite-to-air, $s_{g, \text{air}}$, for the Varian linacs (4 – 18 MeV) and the NPL linac (4 – 19 MeV). $s_{w, \text{air}}$ given by the Burns equation (eq. 1.10 or 1.11) is derived from Monte Carlo simulations of 24 different clinical electron beams, therefore it was considered more accurate to use SPRZnrc to calculate $s_{w, \text{air}}$ for our specific linacs. For the Varian linacs, differences of up to 0.40% were found between the $s_{w, \text{air}}$ values calculated by SPRZnrc and those provided by the Burns equation. For the NPL linac, the largest difference in $s_{w, \text{air}}$ values was 0.72%.

The $s_{g, \text{air}}$ values, unlike the $s_{w, \text{air}}$ values, were below unity for all electron beam energies 4 – 19 MeV. For the Varian linacs at depths between $z_{\text{max}}$ and $R_{50}$, the $s_{g, \text{air}}$ values ranged from 0.9521 to 0.9844 for the 4 MeV beam down to 0.8934 to 0.9498 for the 18 MeV. For the NPL linac at depths between $z_{\text{max}}$ and $R_{50}$, the range was 0.9531 to 0.9853 for the 4 MeV beam down to 0.9030 to 0.9542 for the 19 MeV beam.

Electron perturbation correction factors, $p_{\text{cav}}, p_{\text{wall}}$, and $p_{Q}$ in water for the NACP-02 chamber were calculated for the Varian linac energies 4 – 18 MeV using the EGSnrcMP user code DOSRZnrc. In water at $z_{\text{ref}}$, $p_{\text{cav}}$ values were near unity while $p_{\text{wall}}$ and $p_{Q}$ were both significantly greater than unity with the largest difference being 1.68% and 2.03% respectively for the 4 MeV beam. Generally, the perturbation factors were farther from unity for the lower energy beams. All three perturbation factors increased with depth. At $R_{50}$ for the energies 4 – 18 MeV, $p_{\text{cav}}$ values ranged from 1.0636 to 1.0123, $p_{\text{wall}}$ values ranged from 1.1566 to 1.0402, and $p_{Q}$ values ranged from 1.2301 to 1.0530.
Electron perturbation correction factors, $p_{\text{cav}}$, $p_{\text{wall}}$, and $p_Q$ in graphite for the NACP-02 chamber were calculated for the Varian linac energies $4 - 18$ MeV at depths between $z_{\text{ref}}$ and $R_{50}$ and for the NPL linac energies $4 - 19$ MeV only at $z_{\text{ref}}$. For the Varian linacs at $z_{\text{ref}}$, $p_{\text{cav}}$ ranged from $0.9938 - 1.0004$, $p_{\text{wall}}$ ranged from $1.0069 - 1.0216$, and $p_Q$ ranged from $1.0052 - 1.0153$. The NPL beams had similar variations in their perturbation factors. At $z_{\text{ref}}$, $p_{\text{cav}}$ ranged from $0.9898 - 0.9969$, $p_{\text{wall}}$ ranged from $1.0084 - 1.0148$, and $p_Q$ ranged from $0.9991 - 1.0107$. For the Varian linac at depths deeper than $z_{\text{ref}}$, $p_{\text{cav}}$ and $p_Q$ in graphite like in water, increased in value up to $1.0867$ and $1.0573$ respectively for the $4$ MeV beam. However, unlike water, $p_{\text{wall}}$ in graphite decreased with depth down to $0.9730$ also for the $4$ MeV beam.

For the NACP-02 electron perturbation correction factors in water, comparisons at $z_{\text{ref}}$ for the Varian electron beams with Zakikhani’s work (2006) showed differences of up to $0.71\%$ for $p_{\text{cav}}$, $0.60\%$ for $p_{\text{wall}}$, and $0.49\%$ for $p_Q$. The discrepancies in $p_{\text{cav}}$ values were likely due to the differences in the values of ECUTS used for the simulations. Zakikhani used ECUTS of $521$ keV for calculations in SPRRZnrc and DOSRZnrc while calculations in this work used $521$ keV for SPRRZnrc and $512$ keV in dose scoring and immediate surrounding regions for DOSRZnrc. Although not thoroughly studied, it was generally assumed that the choice of $521$ keV or $512$ keV would not make a large difference in dose determinations. However, at least for the $6$ MeV beam, excellent agreement of within $0.09\%$ or less was achieved for the $p_{\text{cav}}$ perturbation factors once our ECUTS matched Zakikhani’s. A more thorough investigation is required before firm conclusions can be made about the accuracy and impact of a $512$ keV ECUT vs. a $521$ keV ECUT. For the $p_{\text{wall}}$ and $p_Q$ values, the discrepancies were likely caused by the lower ECUT values as well as the $35\%$ increase in the mass density of the chamber front window of this work.

Perturbation factors for the NACP-02 chamber in water for the Varian linac energies were also compared with Zakikhani’s values at $R_{50}$. Both sets of results showed perturbation factors increase with depth but discrepancies between the data sets were larger than at $z_{\text{ref}}$ up to $1-2\%$. This is no surprise as differences in the calculation setup
will be amplified in the high gradient region of a PDD curve. Even our tuned chamber model, which produced perturbation factors similar to the sacrificed chamber model at \( z_{ref} \), became inadequate at \( R_{50} \) and underestimated the values by 1.3-1.4%. We conclude that if sufficiently detailed chamber specifications are unattainable from the manufacturer, tuning the Monte Carlo chamber model against backscattering measurements is an important step in ensuring the validity of the Monte Carlo calculations in regions near charged particle equilibrium such as at \( z_{ref} \). In regions away from charged particle equilibrium, tuning the chamber model is inadequate and only precise specifications are acceptable.

A major difference between graphite and water was that \( p_{wall} \) decreased with depth in graphite while it increased with depth in water. It was determined that the increase seen in the \( p_{wall} \) value with depth in water was due solely to not having scaled for the water equivalent thickness of the NACP-02 front window when positioning the effective point of measurement of the chamber in case c. As \( p_{wall} \) is the ratio of doses in case b over case c, the failure to scale the front chamber window placed the effective point of measurement of the case c tuned chamber model 0.06 cm (in water equivalent thickness) downstream of case b and hence case c received less and less dose relative to case b at deeper depths. When scaling for the water equivalent thickness of the front window was taken into account, the \( p_{wall} \) in water decreased in value with depth similar to the \( p_{wall} \) values in graphite. For example at \( R_{50} \) in the 6 MeV Varian electron beam, \( p_{wall} \) in water had a value of 1.0930 if no scaling had been performed. With scaling, the new value of \( p_{wall} \) at \( R_{50} \) was 0.9731, 12% lower than the original value.

Scaling was not considered important for the perturbation factors in graphite as the graphite and mylar of the NACP-02 front window would only have led to a positioning error of 0.001 cm for the case c tuned chamber model. Scaling was also found to be unimportant at \( z_{ref} \) because it is close to a region of charged particle equilibrium. A positioning error of 0.06 cm here does not make a significant difference in dose deposited and hence perturbation factors at \( z_{ref} \) are not significantly affected. Finally, scaling or not scaling is irrelevant to clinical applications as the change in beam
quality specifier, $R_{50}$, due to whichever set of perturbation factors is used to correct the PDD curve, is less than 0.05 cm.

For scientific interest, an investigation was done to explain why $p_{\text{wall}}$, when the front window is scaled, decreases with depth in the water phantom. Much effort went into analyzing electron energy spectrums, angular distributions, stopping powers and scattering powers of the various chamber and phantom materials and a simplified hypothesis was proposed. The $p_{\text{wall}}$ value, however, is the result of complex interactions between the side, back, and front walls of the NACP-02 chamber that change with depth in the phantom. Considering its high sensitivity to the positioning of the effective point of measurement and the fact that even a perturbation factor of up to 20% fails to alter the $R_{50}$ of a PDD curve by more than 0.05 cm, the immediate impact on radiotherapy delivery is minimal. The best and most obvious conclusion that can be made at the moment is to construct future ionization chambers with a material that has near phantom equivalent properties to minimize the electron fluence perturbation caused by the chamber walls and to eliminate confusion around scaling the front window for phantom equivalent thickness.

An investigation into why $p_{\text{cav}}$ increases with depth in water and graphite phantoms was also performed. It was revealed that despite the forward moving electrons forming the majority of the particles reaching the air cavity, the backscattered electrons are the dominant influence on the $p_{\text{cav}}$ value. It was hypothesized that at deeper depths, the mean energy and hence the range of the backscattered electrons decreases making the guard ring of the NACP-02 chamber more effective at neutralizing the in-scattering effect. $p_{\text{cav}}$ therefore increases with depth because the obliquity effect becomes dominant.

Using the overall electron perturbation factors calculated at $z_{\text{ref}}$ in water for the NPL beams by Zakikhani (2006) and those calculated at $z_{\text{ref}}$ in graphite in this work, the ratio of water over graphite perturbation factors, $p_{\text{ref,w}}/p_{\text{ref,g}}$, required for the NPL calibration service 4 - 19 MeV were finally obtained. Only the 4 and 12 MeV NPL
electron beams have perturbation factor ratios, at $1.0080 \pm 0.28\%$ and $1.0071 \pm 0.28\%$, significantly different from unity. The other electron beams have $\frac{p_{ref,w}}{p_{ref,g}}$ values that fluctuate no farther than 1 standard deviation away from unity.

Two issues arose during the perturbation factor calculations that could affect $\frac{p_{ref,w}}{p_{ref,g}}$ results. The first, as discussed previously, was the difference in results produced by the choice of 512 keV ECUT (this work) vs. a 521 keV ECUT (Zakikhani). The second unexpected issue was the discrepancy in dose calculations performed on the McGill cluster using a phase space file source vs. those on the NPL cluster using a full beam model source. For backscatter factor simulations, doses calculated at the NPL were up to 1% lower than those calculated at McGill. For perturbation factor simulations, the discrepancies for dose calculations were up to 0.5%. More study of these issues is required before we can be confident in the $\frac{p_{ref,w}}{p_{ref,g}}$ results.
References


Buckley L A, Rogers D W O 2006 Wall correction factors, $P_{\text{wall}}$, for parallel-plate ionization chambers *Med. Phys.* **33** 1788-1796

Burns D T, Ding G X, Rogers D W O 1996 $R_{50}$ as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry *Med. Phys.* **23** 383-388

Ding G X and Rogers D W O 1995 Energy spectra, angular spread, and dose distributions of electron beams from various accelerators used in radiotherapy *National Research Council of Canada Report PIRS-0439*


Huang V W, Seuntjens J, Devic S and Verhaegen F 2005 Experimental determination of electron source parameters for accurate Monte Carlo calculation of large field electron therapy *Physics in Medicine and Biology* 50 779-786


Kawrakow I and Rogers D W O 2006(a) The EGSnrc code system: Monte Carlo simulation of electron and photon transport *National Research Council of Canada Report PIRS-701*

Kawrakow I, Mainegra-Hing E, and Rogers D W O 2006(b) EGSnrcMP: the multi-platform environment for EGSnrc *National Research Council of Canada Report PIRS-877*

Ma C-M and Rogers D W O 2007 BEAMDP Users Manual National Research Council of Canada Report PIRS-0509(C)revA

Mainegra-Hing E, Kawrakow I and Rogers D W O 2003 Calculation of plane-parallel ion chambers in $^{60}$Co beams using the EGSnrc Monte Carlo code Med Phys 30 179-189


Reft C S and Kuchnir F T 2000 Experimental determination of the overall perturbation factor for the NACP chamber in electron beams for $d_{\text{max}} < d \leq d_{80}$ Phys. Med. Biol. 46 N49-N55

Rogers D W O and Bielajew A F 1990 Monte Carlo techniques of electron and photon transport for radiation dosimetry The Dosimetry of Ionising Radiation vol 3 (San Diego: Academic) 427-539
Rogers D W O 2004 Accuracy of the Burns equation for stopping-power ratio as a function of depth and $R_{50}$ Med. Phys. 31 2961-2963


Seuntjens J P, Kawrakow I and Rogers D W O 1999 Accuracy tests of the new EGSnrc Monte Carlo system in the simulation of ion chamber response in low energy photon beams Med. Phys. 23 1121 (abstract)


Wang L L W and Rogers D W O 2007 Monte Carlo study of Si diode response in electron beams Med. Phys. 34 1734-1742

Williams A J, McEwen M R and DuSautoy A R 1998 A calculation of water to graphite perturbation factor ratios for the NACP type 02 ionization chamber using Monte Carlo techniques NPL Report CIRM 13 (Teddington: National Physical Laboratory)

Zakikhani R 2006 Calculated perturbation factors for the NACP-02 plane-parallel ionization chamber irradiated in water by megavoltage electron beams Msc Thesis McGill University, Montreal, Canada