Monte Carlo evaluation of the dosimetric uncertainty in matched 6 MV Elekta and Varian linear accelerators

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PhD, BSc Hons.

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Applied Science (Medical and Health Physics)

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July 2012
Except where acknowledgements are made in the text, all work described in this thesis is that of the author. This thesis has not previously been submitted in whole or in part for any academic award to any Institute or University. The content of this thesis is the result of work carried out since the official commencement date of the approved research program.

Jessica E Lye
Abstract

Every year over 50,000 Australians are treated with radiotherapy. The success of the treatment depends absolutely on accurate dosimetry to ensure that the correct dose is delivered to the tumour. The dose delivered within clinics throughout Australia is traceable, via local dosimetry instruments and protocols, to the National Australian Standard for radiation dose. The Standard is maintained by the Australian Radiation Protection and Nuclear Safety Laboratory, ARPANSA, where this thesis was performed. This thesis employs Monte Carlo modelling techniques and measurement to investigate and ensure that the calibration factors employed within radiation therapy centres around Australia are accurate.

The fundamental dose uncertainty in the calibration chain for therapeutic radiation treatment is in the primary standard calibration of the clinic’s ionization chamber. Any error in the primary standard calibration will transfer directly to the dose delivered to every radiotherapy patient in Australia. The calibration is performed by ARPANSA, which currently provides chamber calibrations based on a $^{60}$Co reference beam. The radiotherapy clinic then requires a generic chamber correction to shift the calibration from $^{60}$Co to their higher energy linac beams. The process of using a generic correction factor adds uncertainty to the dose determination. Calibrating the clinic’s ionization chamber within a similar beam spectrum, or quality, to the user beam, can reduce this uncertainty significantly.

To facilitate a national improvement in therapeutic dosimetry, ARPANSA has installed a clinical linear accelerator (linac) to provide chamber calibrations at the user beam quality. The ARPANSA reference linac is an Elekta Synergy platform linac, which can be tuned to mimic the beam qualities available in Australian clinics, such as those produced by the Varian linac platforms.

Monte Carlo models of a Varian and matched Elekta accelerator have been developed and commissioned. They accurately predict the measured percentage depth dose and profiles, but show significantly different energy spectra, resulting mainly from differences
in target thickness between the two accelerators. The critical question is if the spectral difference between the Varian and the matched Elekta will cause any significant change in a chamber calibration factor. This work calculates the error introduced when using a calibration factor obtained from this Elekta Synergy Platform linac on a Varian high energy platform beam at 6 MV.

To determine the answer a two stage modelling approach was applied. Firstly the graphite calorimeter that is the Australian primary standard of absorbed dose was modelled. Using the commissioned linac models, the calorimetry measurements of absorbed dose to graphite can be converted to absorbed dose to water in a direct Monte Carlo conversion. Using the direct MC conversion removes from the calorimeter response any dependence on the source spectrum. The ionisation chamber calibration factor is then only dependant on the chamber response. The direct MC conversion without a transfer chamber in graphite is also a novel method of realising absorbed dose to water from graphite calorimetry measurements.

The second stage was to model a secondary standard chamber type NE2561. The modelling of the energy correction factor $k_Q$ of a secondary standard NE2561 chamber shows a difference of 0.4 % between the Varian and Varian-matched Elekta beams. Although small, this is a significant discrepancy for primary standard calibrations. Ionisation chambers calibrated on the ARPANSA 6 MV beam may be in error by 0.4% when used on a Varian 6 MV beam. Similar variations may occur with other manufacturers. The work has also investigated the design of a custom flattening filter to precisely match the energy spectrum of the Varian beam on the Elekta platform.

The Monte-Carlo investigation of the $k_Q$ of the secondary standard NE2561 chamber was extended to consider the response with the new flattening filter free (FFF) modality. The $k_Q$ from a modelled Varian FFF beam showed a difference of 0.8 % compared to the 6 MV Elekta with the same beam quality index, $TPR_{20,10}$, (Tissue phantom ratio in water at depths of 20 and 10 cm), and the Elekta FFF beam showed a difference of 0.6 %.
The magnitude of the discrepancy between the Varian FFF beam and the ARPANSA Elekta beam demonstrates that $TPR_{20,10}$ is not sufficient as the sole beam quality specifier to derive calibration factors for flattening filter free beams, and even with standard clinical beams the use of $TPR_{20,10}$ alone can introduce errors of 0.4%.
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Acknowledgements

Monte Carlo calculations were undertaken using supercomputer facilities of the Victorian Partnership for Advanced Computing (VPAC).

Many thanks to Duncan Butler for detailed discussions and help with this work. Thanks to David Burns for important discussion on quality assurance of the Monte Carlo calculations and Alex Merchant for help in implementing the models on the VPAC supercomputer. Thanks also to Peter Johnston, Ivan Williams, and Rick Franich for proof reading the thesis.

Thank-you to Tomas Kron for providing the experimental data from a Varian linac for commissioning the Monte Carlo model. Thank-you to Elekta for providing ARPANSA with specification of their accelerator for modeling purposes under a non-disclosure agreement, and thank-you to Varian Medical Systems for providing RMIT with specifications of their accelerator for modeling purposes under a non-disclosure agreement.
Chapter 1  Introduction

Every year over 50,000 Australians are treated with radiotherapy. The success of the treatment depends absolutely on accurate dosimetry to ensure that the correct dose is delivered to the tumour whilst minimising harmful side effects.

Cancer cells are generally more sensitive to radiation than normal tissue. The acute response of cells to radiation means a few percent change in the dose delivered results in a large change in the fraction of cells destroyed by the radiation. By carefully choosing the dose delivered a lethal dose of radiation can be delivered to the tumour whilst the normal tissue is able to survive. Delivering very precise doses improves the likelihood of curing the cancer whilst avoiding debilitating side effects that compromise quality of life.

The dose delivered within clinics throughout Australia is traceable to the National Australian Standard for radiation dose. The standard is maintained by the Australian Radiation Protection and Nuclear Safety Laboratory, ARPANSA, where this thesis was performed. The final dose delivered to the patient depends on the accuracy of a complex dosimetric process beginning with the primary standard chamber calibration through to the actual treatment delivery. The steps involved in this process are shown in Figure 1.1.

![Figure 1.1 The radiotherapy dosimetric process beginning with the primary standard chamber calibration through to the actual treatment delivery.](image)

The fundamental dose uncertainty in the calibration chain for therapeutic radiation treatment is in the calibration of the clinic's ionization chamber with the primary standard. Any error in the primary standard calibration will transfer directly to the dose delivered to every radiotherapy patient in Australia.
Australian facilities follow the TRS-398 international code of practice (Andreo et al 2001). TRS-398 recommends that the difference in planned to delivered dose be less than ± 3-5 %. This is not easy to achieve. There are many contributions to the uncertainty in delivered dose in the dosimetric chain. To minimize the contribution from the primary standard calibration, ARPANSA aims to calibrate the clinic's chamber with an accuracy of better than 0.5 % (at 1σ). With this accuracy in mind primary standard dose calculation needs to consider uncertainties and corrections down to the order of 0.1 %.

ARPANSA currently provides chamber calibrations based on an absorbed dose to water standard at the $^{60}$Co reference beam quality, $Q_0$. Following TRS-398 the calibration coefficient $N_{D,w,Q_0}$ is converted to the user beam quality using the calculated radiation beam quality correction factors $k_{Q,0}$ (also referred to as $k_Q$ when $^{60}$Co is the reference quality). TRS-398 estimates a standard uncertainty of 1 % in $k_Q$, which is consistent when compared to experimental data (Andreo 2000b, McEwen 2010). More recent estimates of uncertainty in $k_Q$ suggest a lower uncertainty of 0.5 % (Rogers 2009).

Calibrating with a similar beam spectrum, or quality, to the user beam, can eliminate the large uncertainty resulting from using a generic beam quality correction, and TRS-398 recommends calibrating directly at the users beam quality. To facilitate a national improvement in therapeutic dosimetry, ARPANSA has installed a clinical linear accelerator to provide chamber calibrations directly at the user beam quality. Other primary standard labs have also moved to direct megavoltage calibrations from a reference linac, and ten National Metrology Institutes are registered in the Bureau International des Poids et Mesures (BIPM) ongoing key comparison of absorbed dose to water for accelerator photon beams (Key Comparison BIPM.RI(I)-K6).

ARPANSA has installed an Elekta Synergy Platform linac. In Australia there are currently linacs manufactured by Varian, Elekta, Siemens and Phillips, the majority of which are Varian. Each manufacturer uses a unique set of filters and initial electron energy to produce the clinical beam resulting in different spectra even though the linacs may be characterised by the same TPR$_{20,10}$. It is important to determine if any error is introduced into the primary standard calibration factor when using the ARPANSA Elekta linac for users with linear accelerators from other manufacturers.
This thesis employs Monte Carlo modelling techniques and measurement to minimise uncertainties in the calibration factors determined by ARPANSA with the new linac, and ultimately ensure that more accurate doses are delivered to patients.

1.1 Background on the new ARPANSA linear accelerator

The ARPANSA reference linac has a larger than usual range of photon energies, 4, 6, 10, 15, 18, and 24 MV and a large range of electron energies, 4, 6, 8, 9, 10, 12, 15, 18, 20, and 22 MeV. There is also the possibility of multiple 6 and 18 MV energies, tuned to slightly different beam qualities as defined by their TPR$_{20,10}$. Figure 1.1.1 shows the spread of 6 MV beam qualities across Australia in 2009 (Brown et al 2010) including their spread according to manufacturer. 6 MV is the most common photon beam accounting for 55% of photon beams across Australia. Of the 6 MV beams, 66% are Varian, 18% are Elekta, 14% are Siemens, and 1% is Phillips (note that Phillips and Elekta linacs are produced at the same factory). The TPR$_{20,10}$ are distributed according to manufacturer with Varian beams displaying lower average energy than the Elekta beams and Siemens lying in between. The standard ARPANSA 6 MV Elekta beams have a TPR$_{20,10}$ of 0.681. Another beam was tuned to be matched to a typical Varian TPR$_{20,10}$ of 0.671 using data obtained from a local clinic. Both the standard and Varian-matched ARPANSA beams are shown in yellow in Figure 1.1.1.

![Figure 1.1.1 TPR$_{20,10}$ values for 6 MV beam qualities used for radiotherapy in Australia in 2009 including breakdown by manufacturer (Brown 2010).](image)
The standard and Varian-matched 6 MV beams use the same hardware components, but have different incident electron energy and associated beam steering. In contrast to beam matching in a clinical setting, only the percentage depth dose (PDD) were matched and the horns in the profile were ignored. This was for two reasons. Firstly, with significantly different physical targets and flattening filters in the Varian and Elekta machines, it is not possible to match both the PDDs and profiles by changing only the incident electron energy. Secondly, as we are only concerned with measurements on the central axis for reference 10 x 10 cm beams for chamber calibrations, the horns in the profiles are not critical. It is standard practice with primary standard dosimetry to apply a correction factor to account for any small variations from an ideal flat beam in the central portion of the profile.

Figures 1.1.2 and 1.1.3 show the results from the beam matching process. Figure 1.1.2 (a) compares the measured PDD of the ARPANSA beam before tuning the electron energy to the measured PDD from a local hospital with a Varian linac. Both PDDs were measured with a CC13 chamber in a Scanditronix Wellhöfer water tank. The inset shows the local difference between the two PDDs and a large difference of 6% over the 40 cm is noted. Figure 1.1.2 (b) compares the measured PDD of the ARPANSA beam after adjusting the electron energy to match the measured PDD of the Varian beam. The inset shows the excellent agreement within 1% between the two PDDs. Figure 1.1.3 shows the 10 x 10 cm profiles of the actual Varian beam and our Varian-matched beam. Even though no attempt was made to match the profiles, the central 2 cm show good agreement between the two beams.
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1.2 Outline of the thesis

The aim of this thesis is to ensure that accurate calibration factors are provided to radiotherapy clinics when moving to the new linac-based primary standard calibrations. Specifically, this thesis quantifies the error introduced when using a calibration factor from the ARPANSA Elekta linac on a Varian high energy platform beam at 6 MV.

Chapter 2 considers in detail the choice of EGSnrc parameters for accurate modelling of the linacs. The choice of electron and photon cutoff energy and the associated PEGS4 data, changes from the default EGSnrc transport parameters, and range rejection options are explored weighing up accuracy of the model compared to measured data against the related time costs.

Chapter 3 and 4 discuss the commissioning of the linac source models against water tank measurements using the parameters discussed in Chapter 2. The Monte Carlo commissioning tolerances are reviewed from literature and defined for the purpose of this thesis. The main
components and geometry of each model are presented and profiles and PDDs from the model are compared to water tank measurements. Chapter 3 presents results from the 6 MV Varian model and Chapter 4 presents results from both the standard 6 MV Elekta model and the 6 MV Varian-matched Elekta model.

Chapter 5 discusses using the source models together with a model of the graphite calorimeter (the Australian primary standard of absorbed dose) to provide a direct conversion from absorbed dose to graphite to absorbed dose to water. The direct Monte Carlo conversion removes from the calorimeter response any dependence on the source spectrum. The ionisation chamber calibration factor is then only dependant on the chamber response, as modelled in the following chapter.

Chapter 6 discusses modelling a NE2561 secondary standard chamber to determine the difference in response to a Varian 6 MV beam and the ARPANSA Varian-matched Elekta beam. The model is validated by comparing the modelled $k_Q$ of the standard ARPANSA 6, 10, and 18 MV beams to a compilation of published measured $k_Q$. The modelled response of the NE2561 with the Varian source model is compared to the modelled response with the Varian-matched Elekta source model, showing a difference of 0.4 %. The spectra of the Varian and TPR$_{20,10}$ matched Elekta beams is also clearly different. The target thickness and initial electron energy in the TPR$_{20,10}$ matched Elekta linac model is changed to the values in the true Varian model. The resulting NE2561 simulation showed a response in agreement with the true Varian, confirming that the difference in target thickness between the Varian and TPR$_{20,10}$ matched Elekta beams is behind the difference in spectra and response. A custom flattening filter for the Elekta beam was designed and modelled to exactly match the true Varian Spectra. The resulting NE2561 simulation showed a response in agreement with the true Varian. Potentially a custom flattening filter could be implemented at ARPANSA to mimic a Varian beam more precisely. Finally, the flattening filter free (FFF) modality was investigated by removing the flattening filters from both the Elekta and Varian beam models, and increasing the initial electron energy until the beams were TPR$_{20,10}$ matched to the true Varian. The $k_Q$ from the modelled Varian FFF beam showed a difference of 0.8 % compared to the 6 MV Elekta with the same TPR$_{20,10}$, and the Elekta FFF beam showed a difference of 0.6 %, and the FFF spectra were vastly different to the other beams.
1.3 Publications arising from this work

The new method of deriving absorbed dose to water from graphite calorimetry measurements using a direct Monte Carlo conversion has been used to reevaluate the Australian primary standard for absorbed dose at a $^{60}\text{Co}$ beam quality. A comparison was performed with the BIPM, and the results of the comparison were used to update Australia’s position in the BIPM key comparison database. The results of the comparison have been published in:


Details of the direct MC method including assessment of the associated uncertainties have been described in a second paper submitted to Radiation Protection Dosimetry. The paper has been accepted for publication consideration subject to revision.


A third paper is expected from the direct MC conversion work describing the conversion at megavoltage energies for 6, 10, and 18 MV beams.

A paper describing the modelling of a NE2561 secondary standard chamber to determine the difference in $k_0$ for a Varian 6 MV beam and the ARPANSA Varian-matched Elekta beam has been submitted to Physics in Medicine and Biology. The paper has been accepted for publication consideration subject to revision.

Chapter 2  Selecting EGSnrc parameters

The EGSnrc (Kawrakow 2000) user codes BEAMnrc (Walters et al. 2007), DOSXYZnrc (Ma et al. 2001), and DOSRZnrc (Rogers et al. 2000) have been used in this work. The EGSnrc code has been extensively used for modeling in radiotherapy research and the user codes are tailored to modeling linear accelerators as well as radiotherapy dosimeters and phantoms. Numerous papers have validated the code (see Verhaegen and Seuntjens 2003 and references therein) and it is well documented and the graphical user interfaces (GUI) are particularly user friendly.

The default BEAMnrc/EGSnrc parameters have been selected as a compromise between accuracy of the simulations and speed of calculations. As many users do not have access to a supercomputer the default settings allow linac simulations to be performed on single PC.

The default settings cause some inaccuracies, and to achieve a model matched to the criterion detailed in Chapter 3, it is necessary to change these settings. This chapter examines the effect of changing various BEAMnrc/EGSnrc parameters and the final choice of parameters used in the commissioned models. The following simulations are for a model of a Varian 6 MV beam with incident electron energy of 6.0 MeV.

2.1 PEGS4 data: 521icru or 700icru

The two default PEGS4 data sets containing commonly used materials are “521icru.pegs4dat” and “700icru.pegs4dat”. The difference between the data sets is the cutoff energy for electrons used in generating the PEGS4 data sets, being 521 keV and 700 keV for “521icru.pegs4dat” and “700icru.pegs4dat” respectively. Both data sets use a cutoff energy of 10 keV for photons. The data sets are related to the BEAMnrc/DOSXYZnrc parameters Global electron cutoff energy, ECUT, and Global photon cutoff energy, PCUT. ECUT defines the cutoff energy for electron transport in BEAMnrc/DOSXYZnrc. As soon as an electron's total energy falls below the ECUT, its history is terminated and its energy is deposited locally. Similarly, PCUT defines the cutoff energy for photon transport in BEAMnrc/DOSXYZnrc.

Figure 2.1.1 shows a comparison of the profile at \(d_{\text{max}}\) and the PDD for a 30 x 30 cm\(^2\) field when either “521icru.pegs4dat” or “700icru.pegs4dat” is used in both BEAMnrc and DOSXYZnrc. The profiles are normalized to the central dose and the PDDs are normalized to the dose at 10 cm. Using “700icru.pegs4dat” underestimates the horns in the profile and also underestimates the gradient of the PDD. Table 2.1.1 shows the associated CPU time for the two data sets. In all
BEAMnrc simulations $1 \times 10^7$ primary histories were used combined with directional bremsstrahlung splitting with a splitting number of 500, and in all DOSXYZnrc simulations $1 \times 10^{10}$ primary histories were used. Using “521icru.pegs4dat” increases the time for the DOSXYZnrc runs, but the runs can still be completed overnight.

In commissioning the linac models, “521icru.pegs4dat” with some additional user defined materials appended, ECUT = 521 keV, and PCUT = 10 keV were used.

Table 2.1.1 Comparing the time taken when changing the PEGS4 data and ECUT and PCUT in both BEAMnrc and DOSXYZnrc files.

<table>
<thead>
<tr>
<th>EGSnrc Option</th>
<th>BEAMnrc # of parallel CPU</th>
<th>BEAMnrc Time/CPU (hours)</th>
<th>DOSXYZnrc # of parallel CPU</th>
<th>DOSXYZnrc Time/CPU (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECUT = 0.700 MeV</td>
<td>10</td>
<td>0.2</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>ECUT = 0.521 MeV</td>
<td>10</td>
<td>0.2</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 2.1.1 Comparing (a) the profiles and (b) the PDDs of a 30x30 cm field when changing the PEGS4 data and ECUT and PCUT in both BEAMnrc and DOSXYZnrc files.
2.2 EGSnrc parameters

In both BEAMnrc and DOSXYZnrc there are EGSnrc beam transport parameters that can be chosen. There were four parameters that were investigated that potentially needed to be changed from their default settings.

Brems angular sampling = KM (Default=Simple)

Brems angular sampling defines how the emission angle of bremsstrahlung photons is determined. The default “Simple” option uses only the leading term of the Koch-Motz distribution while the “KM” option uses the complete modified Koch-Motz 2BS distribution (Koch and Motz 1959, Kawrakow I. and Rogers 2006). Using “Simple” can affect the proper handling of bremsstrahlung kinematics at low energies (Ali et al 2012).

Pair angular sampling = KM (Default=Simple)

Pair angular sampling defines how the emission angle of pair production is determined. The default “Simple” option uses only the leading term of the Koch-Motz distribution while the “KM” option uses the complete 2BS Koch-Motz distribution (Koch and Motz 1959, Kawrakow I. and Rogers 2006).

Photoelectron angular sampling = On (Default=Off)

Photoelectron angular sampling defines how the emission angle of photo-electrons is determined. The default “Off” option uses the direction of the “mother” photon while the “On” option uses Sauter’s formula (Sauter 1931, Kawrakow I. and Rogers 2006).

Atomic relaxations = On (Default=Off)

Atomic relaxations determines if shell vacancies created after photo-absorption events are relaxed with emission of fluorescent X-rays, Auger and Koster-Cronig electrons (Kawrakow I. and Rogers 2006).

Various combinations of the above parameters are changed from their default:

In Option1: Brems angular sampling was changed to KM in BEAMnrc, not in DOSXYZnrc.
In Option 2: Brems angular sampling was changed to KM, Pair angular sampling was changed to KM, Photoelectron angular sampling was changed to KM, and Atomic relaxations was turned on in BEAMnrc, not in DOSXYZnrc

In Option 3: Brems angular sampling was changed to KM, Pair angular sampling was changed to KM, Photoelectron angular sampling was changed to KM, and Atomic relaxations was turned on in both BEAMnrc and DOSXYZnrc

Figure 2.2.1 shows a comparison of the profile at $d_{\text{max}}$ and the PDD for a 30 x 30 field for the three options described above versus the default parameters. All the options show an increase in the horns in the profile from the default, but there is no significant difference between the three options. The parameter that makes the biggest difference is changing Brems angular sampling to KM in BEAMnrc. Table 2.2.1 shows the associated simulation time with the various options. Option 2 and 3 increase the simulation time considerably without changing the profile or PDD.

In commissioning the linac models, Brems angular sampling was set to KM in BEAMnrc, while Pair angular sampling, Photoelectron angular sampling and Atomic relaxations were left at their default settings.

<table>
<thead>
<tr>
<th>EGSnrc Option</th>
<th>BEAMnrc # of parallel CPU</th>
<th>BEAMnrc Time/CPU (hours)</th>
<th>DOSXYZnrc # of parallel CPU</th>
<th>DOSXYZnrc Time/CPU (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>10</td>
<td>0.2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Option 1</td>
<td>10</td>
<td>0.4</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Option 2</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Option 3</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 2.2.1 Comparing (a) the profiles and (b) the PDDs of a 30x30 cm field when changing the EGSnrc parameters in both BEAMnrc and DOSXYZnrc files.
2.3 Range Rejection

Range rejection is a time saving option where the range of a charged particle is calculated and if it does not have sufficient energy to leave the current region, its history is terminated and its energy is deposited locally. This introduces an approximation because it assumes that any bremsstrahlung photons that would have been created by the particle would also not leave the current region. To avoid this error the variable ESAVE can be used that sets the maximum energy that a particle can have for range rejection to be used.

Figure 2.3.1 shows a comparison of the profile at $d_{\text{max}}$ and the PDD for a 30 x 30 cm$^2$ field when range rejection is on or off in the target. The range rejection was set to “on with varying ECUTRR”. Ignoring bremsstrahlung production in the target could lead to inaccuracies and to investigate this ESAVE in the target was set to either 0.521 MeV or 2 MeV. This effectively turns the range rejection on or off in the target. A small difference of about 0.5 % is seen in the horns when range rejection is on in the target (i.e. ESAVE = 2 MeV). No difference could be seen in the PDDs, showing the lack of sensitivity of PDDs to variable change. Table 2.3.1 shows the associated simulation time with and without range rejection in the target. Turning range rejection off in the target increases the time for the BEAMnrc runs, but the simulations can still be completed overnight.

In commissioning the linac models, range rejection was off in the target by setting ESAVE to 0.521 MeV.

Table 2.3.1 Comparing the time taken when range rejection is turned on and off in the target.

<table>
<thead>
<tr>
<th>EGSnrc Option</th>
<th>BEAMnrc # of parallel CPU</th>
<th>BEAMnrc Time/CPU (hours)</th>
<th>DOSXYZnrc # of parallel CPU</th>
<th>DOSXYZnrc Time/CPU (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Rejection On</td>
<td>10</td>
<td>0.4</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Range Rejection Off in target</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 2.3.1 Comparing (a) the profiles and (b) the PDDs of a 30x30 cm field when the range rejection is turned on and off in the target.
2.4 Selected MC transport parameters

The selected MC transport parameters used in the BEAMnrc linac source model and the DOSXYZnrc water phantom model are listed in Table 2.4.1.

Table 2.4.1 Selected MC transport parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BEAMnrc source model</th>
<th>DOSXYZnrc homogeneous phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global ECUT</td>
<td>0.521</td>
<td>0.521</td>
</tr>
<tr>
<td>Global PCUT</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Global SMAX</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>ESTEPE</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>XIMAX</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Boundary crossing algorithm</td>
<td>EXACT</td>
<td>PRESTA-I</td>
</tr>
<tr>
<td>Skin depth for BCA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Electron-step algorithm</td>
<td>PRESTA-II</td>
<td>PRESTA-II</td>
</tr>
<tr>
<td>Spin effects</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>Brems angular sampling</td>
<td>KM</td>
<td>Simple</td>
</tr>
<tr>
<td>Brems cross sections</td>
<td>BH</td>
<td>BH</td>
</tr>
<tr>
<td>Bound Compton scattering</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Pair angular sampling</td>
<td>Simple</td>
<td>Simple</td>
</tr>
<tr>
<td>Photoelectron angular sampling</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Rayleigh scattering</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Atomic relaxations</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Electron impact ionization</td>
<td>Off</td>
<td>Off</td>
</tr>
</tbody>
</table>
Chapter 3  The Varian Trilogy model

The first step in modelling how well the ARPANSA Varian-matched Elekta beam reproduces the response of a NE2561 chamber to a true Varian beam is to develop and commission models of both linacs. This chapter discusses the implementation of the true Varian linac model and the commissioning of the linac source model against water tank measurements.

3.1 Monte Carlo model of the 6 MV Varian Trilogy

![Diagram of Varian Trilogy model](image)

**Figure 3.1.1** Schematic of geometry and component modules used in BEAMnrc for modelling the Varian linac.

The EGSnrc user code BEAMnrc was used to model the Varian linac. A phase space file output at 100 cm from the target was then used as the source for the subsequent model of the water phantom using the user code and DOSXYZnrc. The ionisation chamber that is used to measure the PDDs was not modelled. The possibility to model the ion chambers in water exists using the
C++ cavity and EGSchamber codes, however it involves considerably more work. DOSXYZnrc has a user-friendly graphically user interface that allows rapid coding of new simulation geometries. With DOSXYZnrc the entire PDD curve and profiles at every depth is obtained from a single simulation, as opposed to running separate simulations of the ion chamber at every depth required. Using the effective point of measurement to convert the current obtained from the chamber to dose is highly accurate (better than 0.1 %) away from the build-up region (Tessier and Kawrakow 2010). In this work only dose at depth is considered and all PDD matching is done at depths greater than $D_{max}$ to avoid errors caused by modelling the dose directly and relying on EPOM to convert the measured PDI to PDD.

A schematic of the geometry of the beam shaping devices and the selected component modules of the Varian linac are shown in Figure 3.1. Geometries and materials in the figure are approximated from the detailed specifications of the accelerator’s head components provided by the manufacturer (Varian 2012). Exact details of the geometry are not reproduced in this thesis due to confidentiality, but can be obtained by contacting the manufacturer directly. The electron source was modelled as a parallel circular beam with Gaussian radial distribution. The selected MC transport parameters used in the BEAMnrc source model are listed in Table 2.4.1.

$1 \times 10^8$ primary histories were used for a 10 x 10 cm field, combined with directional bremsstrahlung splitting with a splitting number of 500 and a splitting field radius of 11 cm at 100 cm source to surface distance. The linac simulations for a 10 x 10 cm field took approximately 90 CPU hours to run using the Victorian Partnership for Advanced Computing (VPAC) Tango supercomputer and produced $1 \times 10^8$ particles. Tango utilizes AMD Shanghai 2.5 GHz quad core processors.

### 3.2 Monte Carlo commissioning tolerances

The commissioning process and tolerances for a MC model of a linac are well established in the literature (Hartmann Siantar et al 2001, Rangel et al 2007, Verhaegen et al 2003, Mesbahi et al 2001), and this is used as a basis for our linac modelling. The general methodology is that experimental dose profiles at different depths and percentage depth dose (PDD) curves in a water phantom for a 10x10 cm field and a larger field, e.g. 30x30 cm, are compared to MC profiles and PDDs for commissioning. There are two free parameters that are tuned to match...
the profiles and PDDs; the incident electron energy, and the width of the electron beam on the target. The two field sizes, and in particular matching the horns in the larger field size case, are important in the iterative determination of these two parameters.

The suggested tolerances from various references are listed below:

PDD local differences <2% (at depths greater than $d_{\text{max}}$)

**A. Mesbahi et al., Applied Radiation and Isotopes, 64 p 656–662(2006):**
Central region local difference <2 %
Penumbra region local difference <10%
Outside beam edge local difference <30%

Build up region local difference < 7%
PDD local difference < 1.5% (at depths greater than $d_{\text{max}}$)
Horns local difference < 2 %
Tail with respect to central axis dose < 3.5%
Penumbra < 1mm width between 20% and 80% levels
Field width < 0.5 mm width

**C. L. Hartmann Siantar et al., Med. Phys. 28 issue 7, p 1322 (2001):**
PDD local difference < 2% (at depths greater than $d_{\text{max}}$)
Central region local differences < 2 %
Penumbra region < 1mm
Outside penumbra region local differences <15% (<1% of central axis dose)

Table 3.2.1 gives the matching tolerances used in this work compiled from the combined recommendations of Hartmann Siantar et al 2001, Rangel et al 2007, Verhaegen et al 2003 and Mesbahi et al.
Table 3.2.1 Matching tolerances compiled from (Hartmann Siantar et al. 2001, Rangel et al. 2007, Verhaegen et al. 2003, Mesbahi et al.).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Matching tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD local difference</td>
<td>&lt;1.5-2 % (at depths greater than $d_{\text{max}}$)</td>
</tr>
<tr>
<td>Central region local difference</td>
<td>&lt; 2 %</td>
</tr>
<tr>
<td>Outside beam edge with respect to central dose</td>
<td>&lt; 3 %</td>
</tr>
<tr>
<td>Penumbra width</td>
<td>&lt; 1 mm between 20 % and 80 % levels</td>
</tr>
<tr>
<td>Field width</td>
<td>&lt; 0.5 mm</td>
</tr>
</tbody>
</table>

3.3 Commissioning the Varian model against water tank measurements

The phase space file output at 100 cm from the target was used as the source for a DOSXYZnrc simulation of the 60 x 60 x 45 cm water phantom. The voxels in the z direction were 0.2 cm deep for the first 4 cm and 0.5 cm subsequently. For 10 x 10 cm fields the voxels were 0.2 x 0.2 cm over the central 20 cm with 20 cm slabs on either side. For 30 x 30 cm fields the voxels were 0.5 x 0.5 cm over central 40 cm with 10 cm slabs on either side. The selected MC transport parameters used in the DOSXYZnrc water phantom model are listed in Table 2.4.1. $1 \times 10^{10}$ primary histories were used, and the "HOWFARLESS" option was used. A single simulation took 120 CPU hours to run and was run on 20 parallel processors of the VPAC supercomputer, taking approximately 6 hours to run in real time.

The measurements were taken with a Scanditronix Wellhöfer Blue Phantom scanning water tank with a CC13 ionization chamber. The modelled profiles have been convolved with a 5mm FWHM Gaussian to approximate the size of the ionization chamber used in the experimental profile measurements.

The best agreement was found with an incident electron energy of 6.1 MeV for the Varian model. The model used a 0.5 mm FWHM source size and a monoenergetic source. This was also compared to a model with a spectrum source with a Gaussian spread of 0.5 MeV and no difference was observed. Figures 3.3.1, 3.3.2, and 3.3.3 show the comparison of measured and modelled profiles for the 10 x 10 cm field size at a depth of $d_{\text{max}}$, 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose (+/- 2 % is shown by the dashed red lines). The difference curves are within the tolerances...
from Table 3.2.1. Note that the difference curves show larger deviations in the penumbra region, due to the higher difficulty in modelling and measuring in this high dose gradient region. This common problem is accounted for in the tolerances in Table 3.2.1 by matching to penumbra width rather than local dose difference in the penumbra region. Figure 3.3.4 shows the comparison of measured and modelled PDD curves of the 10 x 10 cm field. The inset is the local difference between the measured and modelled curves showing excellent agreement.

Figures 3.3.5, 3.3.6, and 3.3.7 show the comparison of measured and modelled profiles for the 30 x 30 cm field size at a depth of $d_{\text{max}}$, 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose. The agreement is not quite as good as the 10 x 10 cm case, with some difference visible in the horns. However the difference curves are within the tolerances from Table 3.2.1. Figure 3.3.8 shows the comparison of measured and modelled PDD curves of the 30 x 30 cm field. The inset is the local difference between the measured and modelled curves showing agreement within the local difference tolerance of 1.5 - 2 %.

**Figure 3.3.1** Comparing measured and simulated 10 x 10 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 1.5 cm. The inset shows the global difference between the measured and simulated values (+/- 2 % is shown by the dashed red lines).
Figure 3.3.2 Comparing measured and simulated 10 x 10 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 10 cm. The inset shows the global difference.

Figure 3.3.3 Comparing measured and simulated 10 x 10 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure 3.3.4 Comparing measured and simulated percentage depth dose curves from a Varian Trilogy incident on a water phantom for a 10 x 10 cm field. The inset shows the local difference.

Figure 3.3.5 Comparing measured and simulated 30 x 30 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 1.5 cm. The inset shows the global difference.
Figure 3.3.6 Comparing measured and simulated 30 x 30 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 10 cm. The inset shows the global difference.

Figure 3.3.7 Comparing measured and simulated 30 x 30 cm dose profiles from a Varian Trilogy incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure 3.3.8 measured and simulated percentage depth dose curves from a Varian Trilogy incident on a water phantom for a 30 x 30 cm field. The inset shows the local difference.
Chapter 4  The Elekta Synergy model

This chapter discusses the implementation of both the standard Elekta linac model and the Varian-matched Elekta model. As in the previous chapter, the linac source models are commissioned against water tank measurements.

4.1  Geometry overview of the 6 MV Elekta Synergy

The EGSnrc user code BEAMnrc was used to model the Elekta linac. Both the standard Elekta 6 MV beam and the Varian-matched Elekta 6 MV beam use the same physical components in both reality and in the model. The only difference between the two beams is the incident electron energy and associated steering. In the model, perfect steering and symmetry is assumed so it is only the incident electron energy that needs to be changed. Divergence of the incident electron beam was not required to achieve a good match (Tonkopi 2005).

A schematic of the geometry of the beam shaping devices and the selected component modules of the Elekta linac are shown in Figure 4.1.1. Geometries and materials in the figure are approximated from the detailed specifications of the accelerator's head components provided by the manufacturer. Exact details of the geometry are not reproduced in this thesis due to confidentiality but can be obtained by contacting the manufacturer directly (Elekta 2012). The electron source was modelled as a parallel circular beam with Gaussian radial distribution. A phase space file output at 100 cm from the target was then used as the source for the subsequent water phantom models using the user code DOSXYZnrc The selected MC transport parameters are the same as those listed in Table 2.4.1.

$1 \times 10^8$ primary histories were used for a 10 x 10 cm field, combined with directional bremsstrahlung splitting with a splitting number of 500 and a splitting field radius of 11 cm at 100 cm source to surface distance. The linac simulations for a 10 x 10 cm field took approximately 100 CPU hours to run using the Victorian Partnership for Advanced Computing (VPAC) Tango supercomputer and produced $1 \times 10^8$ particles.
Figure 4.1.1 Schematic of geometry and component modules used in BEAMnrc for modelling the Elekta linac.
4.2 Commissioning the 6 MV Elekta model, Handbag B

The in-house name for the standard 6 MV Elekta beam is “Handbag B”, referring to the name of the hard drive containing the beam parameters used to drive the linac.

The phase space file output at 100 cm from the target was used as the source for a DOSXYZnrc simulation of the 60 x 60 x 45 cm water phantom. The voxels in the z direction were 0.2 cm deep for the first 4 cm and 0.5 cm subsequently. For 10 x 10 cm fields the voxels were 0.2 x 0.2 cm over the central 20 cm with 20 cm slabs on either side. For 30 x 30 cm fields the voxels were 0.5 x 0.5 cm over central 40 cm with 10 cm slabs on either side. The selected MC transport parameters are the same as those listed in the previous chapter for the water phantom model.

$1 \times 10^{10}$ primary histories were used, and the “HOWFARLESS” option was employed. A single simulation took 120 CPU hours to run and was run on 20 parallel processors of the VPAC supercomputer, taking approximately 6 hours to run in real time.

The measurements were taken with a Scanditronix Wellhöfer Blue Phantom scanning water tank with a CC13 ionization chamber. This was the same type of water phantom and chamber as used for the Varian measurements. The modelled profiles have been convolved with a 5mm FWHM Gaussian to approximate the size of the ionization chamber used in the experimental profile measurements.

The best agreement was found with an incident mean electron energy of 6.3 MeV for the standard Elekta model. This value is higher than that of 5.8 MeV found by Tonkopi et al. 2005 for an Elekta linac with the same $TPR_{20,10}$ of 0.681. However the value of 6.3 MeV is close to that of 6.5 MeV provided by the manufacturer together with their detailed specifications of the accelerator’s head components (Elekta 2012). The model used a 0.5 mm FWHM source size and a Gaussian spectrum source with 0.5 MeV FWHM spread. Figures 4.2.1, 4.2.2, and 4.2.3 show the comparison of measured and modelled profiles for the 10 x 10 cm field size at a depth of $d_{max}$, 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose ($\pm$ 2 % is shown by the dashed red lines). The difference curves are within the tolerances from Table 3.2.1. Note that the difference curves show larger deviations in the penumbra region, due to the higher difficulty in modelling and measuring in this high dose gradient region. This common problem is accounted for in the tolerances in Table 3.2.1 by matching to penumbra width rather than local dose difference in the...
penumbra region. Figure 4.2.4 shows the comparison of measured and modelled PDD curves of the 10 x 10 cm field. The inset is the local difference between the measured and modelled curves showing a slight gradient that remains within the 1.5-2 % local difference tolerance.

Figures 4.2.5, 4.2.6, and 4.2.7 show the comparison of measured and modelled profiles for the 30 x 30 cm field size at a depth of $d_{\text{max}}$, 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose. The agreement is not quite as good as the 10 x 10 cm case, with some difference visible in the horns, as was the case in the Varian model. However the difference curves are within the tolerances from Table 3.2.1. Figure 4.2.8 shows the comparison of measured and modelled PDD curves of the 30 x 30 cm field. The inset is the local difference between the measured and modelled curves showing agreement within the local difference tolerance of 1.5 - 2 %. Note that similar results were seen in the $y$ direction and for brevity only the one direction is shown here.

**Figure 4.2.1** Comparing measured and simulated 10 x 10 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 1.3 cm. The inset shows the global difference between the measured and simulated values (+/- 2 % is shown by the dashed red lines).
Figure 4.2.2 Comparing measured and simulated 10 x 10 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global.

Figure 4.2.3 Comparing measured and simulated 10 x 10 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure 4.2.4 Comparing measured and simulated percentage depth dose curves from the standard Elekta 6 MV beam incident on a water phantom for a 10 x 10 cm field. The inset shows the local difference.

Figure 4.2.5 Comparing measured and simulated 30 x 30 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 1.3 cm. The inset shows the global difference.
**Figure 4.2.6** Comparing measured and simulated 30 x 30 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global difference.

**Figure 4.2.7** Comparing measured and simulated 30 x 30 cm dose profiles from the standard Elekta 6 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure 4.2.8 Comparing measured and simulated percentage depth dose curves from the standard Elekta 6 MV beam incident on a water phantom for a 30 x 30 cm field. The inset shows the local difference between the measured and simulated values.

4.3 Commissioning the 6 MV Elekta model, Handbag D

The in-house name for the Varian-matched 6 MV Elekta B is “Handbag D”, referring to the name of the hard drive containing the beam parameters used to drive the linac in this configuration.

The same model as described in the previous section for the standard Elekta beam was used, except that the incident electron energy was varied. The best agreement was found with an incident mean electron energy of 5.9 MeV. The matched Elekta incident electron energy is 0.4 MeV less than our standard Elekta beam energy of 6.3 MeV, and 0.2 MeV less than the Varian beam energy of 6.1 MeV.

Figures 4.3.1, 4.3.2, and 4.3.3 show the comparison of measured and modelled profiles for the 10 x 10 cm field size at a depth of \( d_{\text{max}} \), 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose (± 2 % is shown by the dashed red lines). The difference curves are within the tolerances from Table 3.2.1. Figure 4.3.4 shows the comparison of measured and modelled PDD curves of the 10 x 10
cm field. The inset is the local difference between the measured and modelled curves showing excellent agreement. It is reassuring that the model reproduces the PDDs and profiles at two different electron energies, without adjustment of any other parameters.

Figures 4.3.5, 4.3.6, and 4.3.7 show the comparison of measured and modelled profiles for the 30 x 30 cm field size at a depth of $d_{\text{max}}$, 5 cm, 10 cm and 20 cm respectively. The inset shows the difference between measured and modelled profiles relative to the central dose. The difference curves are within the tolerances from Table 3.2.1. Figure 4.3.8 shows the comparison of measured and modelled PDD curves of the 30 x 30 cm field. The inset is the local difference between the measured and modelled curves showing agreement within the local difference tolerance of 1.5 - 2 %. Note that similar results were seen in the y direction and for brevity only the one direction is shown here.

![Figure 4.3.1](image)

**Figure 4.3.1** Comparing measured and simulated 10 x 10 cm dose profiles from the Varian-matched Elekta 6 MV beam incident on a water phantom at a depth of 1.3 cm. The inset shows the global difference between the measured and simulated values (+/- 2 % is shown by the dashed red lines).
**Figure 4.3.2** Comparing measured and simulated 10 x 10 cm dose profiles in a water phantom from the Varian-matched Elekta 6 MV beam at a depth of 10 cm. The inset shows the global difference.

**Figure 4.3.3** Comparing measured and simulated 10 x 10 cm dose profiles in a water phantom from the Varian-matched Elekta 6 MV beam at a depth of 20 cm. The inset shows the global difference.
Figure 4.3.4 Comparing measured and simulated percentage depth dose curves in a water phantom from the Varian-matched Elekta 6 MV beam for a 10 x 10 cm field. The inset shows the local difference.

Figure 4.3.5 Comparing measured and simulated 30 x 30 cm dose profiles in a water phantom from the Varian-matched Elekta 6 MV beam at a depth of 1.3 cm. The inset shows the global difference.
Figure 4.3.6 Comparing measured and simulated 30 x 30 cm dose profiles in a water phantom from the Varian-matched Elekta 6 MV beam at a depth of 10 cm. The inset shows the global difference.

Figure 4.3.7 Comparing measured and simulated 30 x 30 cm dose profiles in a water phantom from the Varian-matched Elekta 6 MV beam at a depth of 20 cm. The inset shows the global difference.
Figure 4.3.8 Comparing measured and simulated percentage depth dose curves in a water phantom from the Varian-matched Elekta 6 MV beam for a 30 x 30 cm field. The inset shows the local difference.
Chapter 5  New pathway for graphite calorimetry conversion to absorbed dose to water

In this chapter a Monte Carlo model has been developed of the graphite calorimeter that is the Australian primary standard of absorbed dose. Using the commissioned Elekta linac model described in the previous chapter, we can convert the calorimetry measurements of absorbed dose to graphite to absorbed dose to water in a direct Monte Carlo conversion. Using the direct MC conversion removes from the calorimeter response any dependence on the source spectrum as the detailed model of the Linear accelerator head provides a highly accurate representation of the full spectra removing the need for interpolating quantities from a beam quality index and the associated uncertainties. The ionisation chamber calibration factor is then only dependant on the chamber response. The modelling of the ionisation chamber response to the Varian beam and the Varian-matched Elekta beam, described in the final chapter of this thesis, does not need to include a calorimeter factor when the direct MC conversion method has been used in deriving the chamber calibration factor.

The Australian primary standard for absorbed dose to water is derived from the graphite calorimetry measurements. Prior to 2011, the measured absorbed dose to graphite was converted to absorbed dose to water using the photon fluence scaling theorem, also known as the “dose ratio” method (Huntley et al 1998), and checked with an alternate method, cavity ionization theory (Huntley et al 1998, Wise 2001). In the dose ratio method a secondary standard ionization chamber in a water phantom is calibrated against the calorimeter placed in a scaled geometry. The photon fluence scaling theorem i) requires that the physical dimensions (source to detector distance, beam size, and depth) are scaled in the inverse ratio of the electron densities of the two media, and ii) assumes that Compton scattering is the only significant interaction mechanism between the primary radiation and the two phantom materials. The point i) has the drawback that the source position must be known very accurately, unlike measurements where the calorimeter is placed at the same distance as the chamber so that errors in source position will be correlated and not lead to error in the final calibration factor. The point ii) has the disadvantage that at higher MV energies other interactions such as pair production must be calculated and corrected for. Cavity ionisation theory (CIT) uses a transfer instrument to realise the graphite to water dose conversion. The ionization chamber is placed in a graphite phantom at the same depth and source to detector distance as the calorimeter core, and calibrated in terms of absorbed dose to graphite. The graphite to water absorbed dose
conversion is then performed analytically using the ratio of mean restricted stopping powers and perturbation corrections. As well as the uncertainty in the stopping power ratio, use of a transfer instrument has the drawback that an extra measurement, with its associated uncertainty, is required. This drawback may be compensated by other advantages (Chauvenet et al 1997, Guerra et al 1996).

This direct MC conversion, without a transfer chamber calibrated in graphite, is a novel method to perform the conversion of absorbed dose to water to absorbed dose to graphite. Quality control of the direct Monte Carlo conversion is important and has been achieved by comparing modelled to measured PDDs for both graphite and water. Calibration coefficients of two NE2561 secondary standard chambers derived using the new method showed agreement to within 0.3% of generic chamber calibration coefficients provided by the National Physical Laboratory (United Kingdom). Comparison of calibration factors obtained using the direct MC conversion and using CIT showed agreement to within 0.3%.

5.1 Direct MC dose conversion method

The method follows that used by the National Physical Laboratory (NPL) to convert from graphite to water absorbed dose (Burns 1994, Nutbrown et al 2001, Nutbrown et al 2002) with the modification that ionisation chamber measurements in a graphite phantom are not used, except for validation purposes. In the NPL method a working standard ionisation chamber is measured in graphite and compared against the calorimeter. It is then used as a transfer instrument for water phantom calibrations. In our method, an ionisation chamber is placed in water and compared directly against the calorimeter.

The ARPANSA direct MC dose conversion method is conceptually straightforward: The ionization chamber is calibrated in a water phantom with the chamber at the same distance from the source as the calorimeter core. The graphite core depth is approximately scaled to match the water depth of the chamber in terms of electron density to minimise errors introduced by uncertainty in the MC mass–energy absorption coefficients. The Monte Carlo simulations calculate the ratio of the dose to the calorimeter core to the dose to water at the chamber reference depth.

From the calorimeter measurements the absorbed dose rate to graphite is obtained by:
\[
\dot{D}_{\text{core}} = \frac{P}{m}
\] (5.1.1)

where

\[ P \] = isothermal power calculation
\[ m \] = core mass

This is then converted to the absorbed dose to water rate using the direct MC conversion:

\[
\dot{D}_w = \dot{D}_{\text{core}} \left[ \frac{D_w}{D_{\text{core}}} \right]_{MC}
\] (5.1.2)

where

\[ [D_w/D_{\text{core}}]_{MC} \] = Monte Carlo ratio of absorbed dose to water at a reference depth to absorbed dose to graphite core

The absorbed dose to water calibration factor for an ionisation chamber is then calculated using

\[
N_{D,w} = \frac{\dot{D}_w}{I_w k_{\text{elec}} k_{st} k_{\text{tph}} k_s k_p k_{rn}}
\] (5.1.3)

where

\[ I_w \] = Current from transfer chamber in a water phantom
\[ k_{\text{elec}} \] = Electrometer calibration factor
\[ k_s \] = Sleeve correction
\[ k_{\text{tph}} \] = Temperature, pressure and humidity correction
\[ k_r \] = Recombination correction
\[ k_p \] = Polarity correction
\[ k_r \] = Radial beam non-uniformity correction
This new method has the benefit of the accuracy of Monte Carlo modelling the complete source, calorimeter and phantom geometry. Unlike the scaling theorem it does not assume Compton scattering is the only significant interaction, and precise knowledge of source position is not necessary. The new method is straightforward with no extra graphite phantom measurements required. It does however place more reliance on the MC modelling, and quality assurance of the modelling becomes very important as described in the following sections.

5.2 Monte Carlo model of graphite calorimeter and water phantom

With the source model commissioned within acceptable tolerances as described in Chapter 4, the next step was to establish the Monte Carlo ratio of the absorbed dose to water to the absorbed dose to the graphite core, $[D_{w}/D_{core}]_{MC}$. The phase space file output at 100 cm from the centre of the source was used as the source for a new BEAMnrc simulation of the calorimeter and water phantom. BEAMnrc was chosen as the EGSnrc usercode for the calorimeter and water phantom. BEAMnrc has the advantage of a range of easily implemented geometries to cover the desired geometries of both the cylindrical calorimeter and cubic water phantom with a cylindrical scoring voxel. The selected MC transport parameters the same as those listed in Table 2.4.1 for the BEAMnrc source models. $1 \times 10^{10}$ primary histories were used, and no variance reduction was employed. A single simulation took 200 CPU hours to run and was run on 10 parallel processors of the VPAC supercomputer, taking approximately a day to run in real time.

Figure 5.2.1 shows the geometry of the calorimeter model on the left hand side, and the right hand side shows the geometry used to model the water phantom including the 2.4 mm thick polycarbonate tank window. The calorimeter and water phantom are set up so that the core is at the same distance from the source as 10 cm depth in the water phantom. The dose scoring voxel in the water phantom is the same dimension as the calorimeter core, ensuring that the absorbed dose to water rate, as described in Equation 5.1.2, is the absorbed dose averaged over the central 2 cm diameter core size.
Figure 5.2.1 Schematic of geometry used in BEAMnrc for modelling the calorimeter (left) and the water phantom (right).

The BEAMnrc simulation uses a single FLATFILT component module to model the calorimeter. Figure 5.2.2 shows the exact dimensions and materials used in the model of the calorimeter. For the water phantom simulation two SLAB component modules separated by a BLOCK component module are used. The first SLAB contains the 2.4 mm thick polycarbonate window, and a 9.6 cm thick slab of water with a square width of 30 cm. The BLOCK component module containing the scoring voxel with a 2 cm diameter, 2.75 mm thick cylinder approximated by 20 points, follows this. The final component module contains a 20 cm thick water slab.
Figure 5.2.2 Dimensions and materials used in BEAMnrc for modelling the calorimeter.
5.3 Corrections

A series of corrections are applied to calculate \( N_{D,w} \) as described in equation (5.1.3). A brief description of each correction is included below. Note that no gap correction is required as the MC model of the core dose includes details of the gaps between the concentric bodies of the calorimeter.

\[ k_{sl} = \text{Sleeve correction} \]

The sleeve correction is set to unity as the calibration factor is considered to be for the combined chamber plus sleeve.

\[ k_{tph} = \text{Temperature, pressure and humidity correction} \]

The ionization chamber current is corrected to reference conditions: 20°C, 101.325 kPa, and 50% humidity.

\[ k_s = \text{Recombination correction} \]

This is measured for each individual chamber using the two voltage method.

\[ k_p = \text{Polarity correction} \]

This is measured for each individual chamber by changing the polarity.

\[ k_n = \text{Radial beam non-uniformity correction} \]

This was obtained experimentally from water tank profiles. The MC ratio of graphite calorimeter core dose to water dose converts the absorbed dose to graphite to water over the dimension of the calorimeter core. Equation 2 therefore gives the absorbed dose to water rate over the central 2 cm diameter at 10 cm depth. The ionization chamber will have a different dimension and the beam non-uniformity correction corrects for the difference in beam profile in water between chamber and calorimeter core dimension using the methodology described in (Delaunay et al 2007).

\[ k_{ax} = \text{Axial beam non-uniformity correction} \]

This corrects for the difference between the dose averaged over calorimeter core size in the axial direction to the dose at the reference depth. This was calculated to be less than 0.01 % and assumed to be negligible.
### 5.4 Evaluating uncertainty in the MC ratio

#### Table 5.4.1 Relative standard uncertainties for the determination of $[D_w/D_{\text{core}}]_{\text{MC}}$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>ARPANSA relative standard uncertainty$^{(1)}$</th>
<th>100 $u_{iA}$</th>
<th>100 $u_{iB}$ graphite</th>
<th>100 $u_{iB}$ water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncertainty in the geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of graphite plates, density of water</td>
<td></td>
<td>0.07</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Calorimeter density</td>
<td></td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Calorimeter vacuum gaps</td>
<td></td>
<td></td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty due to MC code</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDD gradient match and associated uncertainties</td>
<td></td>
<td>0.15</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty in simulations</td>
<td></td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Combined uncertainty in $[D_w/D_{\text{core}}]_{\text{MC}}$</strong></td>
<td></td>
<td>0.10</td>
<td>0.32</td>
<td>0.33</td>
</tr>
</tbody>
</table>

$^{(1)}$ expressed as one standard deviation

$u_{iA}$ represents the relative uncertainty estimated by statistical methods, type A

$u_{iB}$ represents the relative uncertainty estimated by other methods, type B.

Both types are shown in the table $\times$ 100, as a percentage value.

#### Uncertainty in the geometry

Where we have estimates of density and thickness uncertainties, we calculate the effect on the absolute dose at the reference depths by scaling the depth to approximate changing the density in homogeneous graphite and water phantoms. For an increase in density of 1%, the dose at 6 cm in graphite will change by -0.42% and at 10 cm in water by -0.54%. Our estimated uncertainty in the density of our graphite plates, 0.17 % (Huntley et al 1998), and for water, 0.05 % (due to range of laboratory temperature), leads to uncertainties in $[D_w/D_{\text{core}}]_{\text{MC}}$ of 0.07 % and 0.03%, respectively.

We cannot measure the calorimeter density directly so we estimate the uncertainty to be 3 % based on the measured spread of densities in our graphite plates. The depth from the back of the last plate to the centre of the core is 0.47 cm, approximately a twelfth of the reference depth.
Our estimated uncertainty of 3%, reduced by a factor of 12, leads to uncertainty in $[D_w/D_{\text{core}}]_{MC}$ of 0.10%.

The vacuum gap has been modelled to give a 0.6% shift compared to solid graphite. Assuming an uncertainty of 0.1 mm in the 0.65 mm gap leads to an uncertainty in $D_{\text{core}}$ of 0.06%.

**Uncertainty in the MC code**

To determine the uncertainty in the MC code we compare the measured PDD to the calculated PDD. We calculate the local difference of the measured to MC PDD at depths greater than $d_{\text{max}}$. Since the two PDDs are close, the difference is approximately linear with depth. The gradient of a fit to the local difference with depth, in units of %/cm, is our measure of agreement between the MC PDD and the measured one.

As the measured and MC PDDs have similar shapes the point of matching does not matter. By applying a linear fit over many points the gradient has only a small uncertainty, reducing the effect of the noise on the individual PDD points. We are interested in the steepest part of the curve and consider from 2 – 20 cm in water and 2 – 15 cm in graphite. The maximum graphite depth is limited by our graphite phantom. The measured gradients are 0.017 %/cm and 0.027 %/cm for graphite and water respectively as shown in Figure 5.4.1.

Next we calculate the uncertainty in these gradients by considering the following sources of uncertainty in the modelled PDD; density of graphite and water and uncertainty in the measured PDD; from both effective point of measurement (EPOM) of the chamber and chamber positioning. For a 1% change in density in the homogeneous phantom models, the gradient of the PDD match changes by 0.085 %/cm and 0.066 %/cm for graphite and water respectively. Using 0.17% as the uncertainty in graphite density and 0.05% for water density, we have uncertainties in the gradient of 0.014 %/cm and 0.003 %/cm for graphite and water respectively.

For the EPOM and chamber positioning the uncertainty contribution is estimated by shifting the measured PDD to calculate the effect on the gradient of the PDD match. We have used -0.6r to shift the chamber, and following Tessier and Kawrakow 2010 this could lead to an error in EPOM of 0.2-0.5 mm for chambers with a radius between 3-4mm, with a 10 cm x 10 cm field at 6 MV. We assume a 0.5 mm uncertainty in EPOM giving a change in gradient of 0.020 %/cm and 0.008 %/cm for graphite and water respectively. We estimate the error in the non-random uncertainty in the position of the chamber to be 0.25 mm in graphite and 0.5 mm in water, which
corresponds to an uncertainty in the gradient of 0.010 %/cm and 0.008 %/cm for graphite and water respectively. Combining these uncertainties gives 0.026 %/cm and 0.012 %/cm for the uncertainties in the measured gradients for graphite and water respectively. We sum in quadrature this combined uncertainty to the original gradient of the PDD match to obtain an estimate of the largest gradient that is consistent with our measurements: 0.031 %/cm and 0.030 %/cm for graphite and water respectively. The largest gradient estimate is then used to infer the largest change in the ratio \([D_w/D_{core}]_{MC}\). To relate the largest gradient estimate to the change in dose at the reference depth, we use our earlier result from changing the density that a gradient in graphite of 0.085 %/cm corresponds to a relative change in dose at the reference depth of 0.42%, and that a gradient in water of -0.066 per cm corresponds to a relative change in dose at the reference depth of 0.54 %. Therefore our largest gradient estimate of 0.031 %/cm for graphite corresponds to a 0.15 % shift to the dose in graphite, and 0.030 %/cm for water corresponds to a 0.24% shift to the dose in water. Finally combining all the contributions, we obtain a combined type B uncertainty of 0.36 %. Combining this with the type A MC statistical uncertainty of 0.10% gives a standard uncertainty of 0.33 % in the ratio \([D_w/D_{core}]_{MC}\).
MC evaluation of the dosimetric uncertainty in matched 6 MV Elekta and Varian linacs

Jessica E Lye 2012

Figure 5.4.1 Local differences between measured and modelled PDDs for (a) graphite and (b) water.

5.5 Uncertainty in the calibration factor $N_{D,w}$

Table 5.5.1 Physical constants, correction factors and relative standard uncertainties for the determination of absorbed dose to water at ARPANSA

<table>
<thead>
<tr>
<th>Quantity</th>
<th>ARPANSA value</th>
<th>ARPANSA relative standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100 $u_A$</td>
</tr>
<tr>
<td>$P$ (isothermal power calculation)</td>
<td>-</td>
<td>0.04</td>
</tr>
<tr>
<td>Repeatability</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td>$m$(core mass)/g</td>
<td>1.5622</td>
<td></td>
</tr>
<tr>
<td>$[D_{w}/D_{core}]_{MC}$ (Monte Carlo ratio)</td>
<td>1.0391</td>
<td>0.10</td>
</tr>
<tr>
<td>$k_m$ (radial non-uniformity)</td>
<td>1.0000</td>
<td></td>
</tr>
<tr>
<td>quadratic summation</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>combined relative standard uncertainty</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.5.2 Corrections and combined relative standard uncertainties when measuring transfer chamber responses at ARPANSA.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>ARPANSA value</th>
<th>ARPANSA relative standard uncertainty</th>
<th>100 u_A</th>
<th>100 u_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference distance</td>
<td>100 cm</td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Depth in water</td>
<td>10 cm</td>
<td></td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>k_{sl} (waterproof sleeve)</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>k_{TPH}</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Current measurement</td>
<td>-</td>
<td></td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Monitor chamber measurement</td>
<td></td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>E_{CF} (Electrometer cal factor)</td>
<td>1.0000</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>k_{s} (recombination)</td>
<td>-</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>k_{p} (polarity)</td>
<td>-</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>k_{rn} (chamber radial non-uniformity)</td>
<td></td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>quadratic summation</td>
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<td></td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>combined relative standard uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 5.5.3 Estimated relative standard uncertainties of determining the calibration factor, N_{D,w}, of a transfer chamber at ARPANSA.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>ARPANSA relative standard uncertainty</th>
<th>100 u_A</th>
<th>100 u_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorbed dose rate to water</td>
<td></td>
<td>0.23</td>
<td>0.35</td>
</tr>
<tr>
<td>transfer chamber measurements</td>
<td></td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>quadratic summation</td>
<td></td>
<td>0.24</td>
<td>0.39</td>
</tr>
<tr>
<td>combined relative standard uncertainty</td>
<td></td>
<td></td>
<td>0.45</td>
</tr>
</tbody>
</table>
5.6 Calculating the gap correction and comparison to literature

Although the gap correction is not required when using the direct MC ratio method, it is useful to calculate the correction and compare to previously published numbers by other primary standard laboratories with graphite calorimeters. This allows quality assurance of the geometry used in the calorimeter model, as the PDD measurements do not test the specific geometry of the calorimeter and the difference between a solid piece of graphite compared to the complicated combination of air, vacuum, mylar and graphite present in a calorimeter.

Figure 5.6.1 shows schematics of the three geometries used to investigate the gap correction. The total gap correction is modeled comparing the dose scored in geometry A (complete calorimeter model) to the dose scored in geometry C (solid slab of graphite). The dose scoring voxel is kept at the same distance in both A and C, but the surface is changed to keep the same depth in graphite with and without gaps. An intermediate geometry was also investigated, geometry B, where the gaps between the plates are retained but the gaps between the core, jacket, shield, and medium are removed. The gap corrections quoted in literature generally investigate this second geometry. Table 5.6.1 shows the results of the gap correction investigation.

Figure 5.6.1 Schematic of the three models used to investigate the gap correction.
Table 5.6.1 Gap correction model results.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dose</th>
<th>Statistical Unc</th>
<th>Gap correction (Dose ratio to Model A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.646 x 10^-17</td>
<td>0.10 %</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>5.682 x 10^-17</td>
<td>0.04 %</td>
<td>1.0063</td>
</tr>
<tr>
<td>C</td>
<td>5.693 x 10^-17</td>
<td>0.04 %</td>
<td>1.0082</td>
</tr>
</tbody>
</table>

The total gap correction from Model C is 1.0082 ± 0.0011. The gap correction from Model B due only to gaps between the core, jacket, shield, and medium is 1.0063 ± 0.0011. It is interesting to note that the gaps between the graphite plates add a further 0.19 ± 0.06 % to the total gap correction. The gap correction from Model B compares favorably with values from the literature. Gap corrections are dependent on energy, field size, and depth in graphite (Seuntjens and Duane 2009). The gap correction increases with depth, decreases with energy, and decreases with field size. There is not an exact match in the literature of the ARPANSA conditions of 10 cm depth at 6 MV for a 10 x 10 cm² field, but approximate comparisons can be made. The gap correction will approximately reduce by 0.1-0.2 % from a $^{60}$Co to 6 MV beam (Wise 2011, Owen and DuSautoy 1991) and increase by 0.2 % from 5 cm depth to 10 cm depth graphite (Seuntjens and Duane 2009). Given these trends an approximate comparison of the ARPANSA gap correction with model B at conditions of 10 cm depth at 6 MV to a gap correction in $^{60}$Co at 5 cm depth is reasonable. Previous calculations of the ARPANSA gap correction (excluding effects from plate gaps) gave $1.0056 ± 0.0004$ for a 10 x 10 cm² field at 5 cm depth in (Wise 2011).

The BIPM key comparison database (KCDB) has reports from BIPM.RI(I)-K4 “Measurement of absorbed dose for Cobalt 60” that contain information on gap corrections of various graphite calorimeters from around the world. These gap corrections are in $^{60}$Co at 5 cm depth for a 10 cm x 10 cm field. The gap corrections compiled from the KCDB are shown in Table 5.6.2. They show reasonable agreement with the gap correction from Model B, $1.0063 ± 0.0011$, due only to gaps between the core, jacket, shield, and medium.
Table 5.6.2  Gap corrections complied from the BIPM.RI(I)-K4 key comparison.

<table>
<thead>
<tr>
<th>Organization</th>
<th>$k_{\text{gap}}$</th>
<th>KCDB Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPL</td>
<td>1.0050</td>
<td><em>Metrologia, 2012, 49, Tech. Suppl., 06008</em></td>
</tr>
<tr>
<td>NMIJ</td>
<td>1.0039</td>
<td><em>Metrologia 48 (2011) Tech. Suppl. 06008</em></td>
</tr>
<tr>
<td>VNIIFTRI</td>
<td>1.0050</td>
<td><em>Metrologia 2010 47 Tech.Suppl. 06003</em></td>
</tr>
<tr>
<td>ENEA-INMRI</td>
<td>1.0064</td>
<td><em>Metrologia 2010 47 Tech.Suppl. 06002</em></td>
</tr>
<tr>
<td>BNM-LNHB</td>
<td>1.0091</td>
<td><em>Metrologia 2005 42 Tech.Suppl. 06006</em></td>
</tr>
</tbody>
</table>

5.7  Comparison to CIT and NPL calibration coefficients

The absorbed dose to water calibration factors of two NE2561 chambers were derived from the same calorimetry measurements using both the direct MC conversion method and cavity ionisation theory (CIT). With CIT the ionization chamber is placed in a graphite phantom at the same depth as the calorimeter core and the chamber is directly calibrated in terms of absorbed dose to graphite. The absorbed dose to water is then calculated from the absorbed dose to graphite using:

$$
\hat{D}_w = \hat{D}_c \frac{I_w [L(\Delta)/\rho]_{w,a}}{I_c [L(\Delta)/\rho]_{c,a}} \frac{[P_{\text{wall}} P_{\text{dis}} P_{\text{cel}}]}{[P_{\text{wall}} P_{\text{dis}} P_{\text{cel}}]}
$$

(5.7.1)

where

$I_c$ = the chamber current in graphite phantom

$\hat{D}_c$ = the dose rate to graphite at the chamber measurement depth

$[L(\Delta)/\rho]_{w,a}$ = ratio of mean restricted stopping power ratios of water and air

$[L(\Delta)/\rho]_{c,a}$ = ratio of mean restricted stopping power ratios of graphite and air

$\rho_{\text{wall}}$ = perturbation correction to account for difference in chamber wall material and phantom material

$\rho_{\text{dis}}$ = displacement correction to account for change in fluence due to chamber air cavity in the phantom

$\rho_{\text{cel}}$ = perturbation correction to account for non air equivalence of central electrode
Double primed factors (”) are evaluated at the reference point in the graphite phantom and unprimed factors are evaluated at the reference point in the water phantom.

The factors in Equation 5.7.1 have been previously evaluated at ARPANSA (Wise 2001).

The calibration factors for the two NE2561 chambers were derived from calorimetry measurements taken in December 2010. The same calorimetry measurements were converted to absorbed dose to water using both the direct MC conversion method or CIT. The chambers’ calibration factors agreed to within 0.3 % as shown in the table below.

**Table 5.7.1** Comparison of CIT to direct MC conversion method

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Ratio of CIT to direct MC conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE2561 s/n 328</td>
<td>0.9977</td>
</tr>
<tr>
<td>NE2561 s/n 238A</td>
<td>0.9964</td>
</tr>
<tr>
<td>Average</td>
<td>0.9971</td>
</tr>
</tbody>
</table>

**Comparison to NPL calibration coefficients**

The chambers were also calibrated at the National Physical Laboratory (NPL) in the UK in 2009. Unfortunately both NE2561 s/n 328 and NE2561 s/n 238A were damaged in 2011 and could not be used for direct comparison with recent calorimetry. An indirect method was used instead where another chamber, the NE2561 s/n 150, was calibrated using measurements from August 2011 – April 2012. The ratio of the response of the NE2561 s/n 150 to NE2561 s/n 238A and 328 had been measured in 2010 at 6 MV. These ratios were used to derive an indirect calibration factor for the NE2561 s/n 238A and 328 from the calibration factor of NE2561 s/n 150.

Both ARPANSA and NPL calibrate chambers with a 10 x 10 field. ARPANSA uses a source to surface distance of 100 cm and a depth of 10 cm while NPL has a source to surface distance of 95 cm and a depth of 5 cm. Table 5.7.2 shows a comparison of the ARPANSA and NPL calibration coefficients. Good agreement within the uncertainty of the ARPANSA measurements is seen. Although this is a promising first result, a direct comparison with the same chambers is necessary before the direct MC conversion method can be used with client’s chambers.
### Table 5.7.2  Chamber calibration factors evaluated at NPL and ARPANSA with direct MC conversion for 6 MV.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>$N_{D,w}$ (mGy/nC)</th>
<th>$N_{D,w}$ (mGy/nC)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ARPANSA</td>
<td>NPL</td>
<td></td>
</tr>
<tr>
<td>NE2561 s/n 328</td>
<td>102.1</td>
<td>102.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>NE2561 s/n 238A</td>
<td>101.8</td>
<td>101.9</td>
<td>-0.1</td>
</tr>
</tbody>
</table>
Chapter 6  Modelling the response of secondary standard NE2561 chamber

Chapter 1 discussed how one of the 6 MV beams of the ARPANSA linac has been approximately matched to a Varian high energy platform 6 MV photon beam. The matching was done on the single beam quality specifier $\text{TPR}_{20,10}$. This was deemed suitable following the work of Andreo 2000a on beam quality specification of high-energy photon beams. In this work it is shown that the water to air stopping power ratios and $\text{TPR}_{20,10}$ are very well correlated for clinical beams and can be fitted with residuals of better than 0.2 % for the majority of the clinical spectra investigated. Substantial changes in the water to air stopping power ratios are observed when changing the target and filter thickness away from standard clinical beams. The author concludes that using $\text{TPR}_{20,10}$ as the unique beam quality specifier for photon beams will result in variations of $k_Q$ of less than 0.5 % for clinical beams, and in the majority of cases will be less than 0.2 %. Larger variations can be expected for non-clinical beams.

In this thesis we are investigating the matching of two specific clinical photon beams using $\text{TPR}_{20,10}$ as the beam quality index. Monte-Carlo modelling methods are used to quantify precisely how well a Varian-matched Elekta beam reproduces the $k_Q$ of a NE2561 chamber to a true Varian beam. The NE2561 chamber was investigated as this is a highly reproducible secondary standard chamber that is used in primary standard calibrations exclusively by NPL, and also has $k_Q$ factors that are very close to NE2571, the most commonly used secondary standard chamber in clinics in Australia.

The following sections discuss the model of a secondary standard NE2561 chamber. The modelled energy correction factor $k_Q$ of the NE2561 chamber shows a difference of 0.4 % between the Varian beam and Varian-matched Elekta beam. Section 6.4 considers the spectra of the two beams. Although the Varian and matched Elekta accelerator show well matched PDDs, the have significantly different energy spectra, resulting mainly from differences in target thickness between the two accelerators.

In Section 6.6 a custom flattening filter to precisely match the energy spectrum of the Varian beam on the Elekta Synergy platform linac is designed and modelled, showing that it is possible to match the Varian spectra with a customized Elekta beam.
The final section of this chapter investigates the chamber response to the new flattening filter free (FFF) modality. The $k_Q$ from a modelled Varian FFF beam shows a difference of 0.8 % compared to the 6 MV Elekta with the same TPR$_{20,10}$, and the Elekta FFF beam showed a difference of 0.6 %. The magnitude of the discrepancy between the Varian FFF beam and the ARPANSA Elekta beam implies that accurate calibrations of FFF beams cannot simply rely on interpolating TPR$_{20,10}$ to derive calibration factors measured with standard beams.

### 6.1 Monte Carlo model of NE2561 chamber

The response of a NE2561 secondary standard chamber was modelled using the EGSnrc user code DOSRZnrc. This model is used to investigate the change in $k_Q$ when using phase space files from the Varian linac or the matched Elekta linac. The chamber’s response was calculated by scoring the ratio of the dose deposited in the air cavity (corresponding to the measured charge), to the dose deposited in water. Chambers are calibrated at ARPANSA with respect to their geometrical centre, as opposed to their effective point of measurement, for ease of clinical use. The air cavity dose is compared to the dose deposited in a homogeneous water phantom in the same volume and position as the air cavity to give a relative $k_Q$ that is equivalent to the calibration geometry:

$$k_Q \propto \frac{D_w}{D_{air}}$$

(1)

Absolute $k_Q$ is calculated from the ratio of the relative $k_Q$ for a particular energy to the relative $k_Q$ for $^{60}$Co:

$$k_Q = \frac{D_{w,Q}}{D_{air,Q}} \cdot \frac{D_{air,Q_0}}{D_{w,Q_0}}$$

(2)

The EGSnrc mortran based usercode DOSRZnrc was chosen over the C++ cavity and EGSChamber codes because it has an extremely user-friendly graphically user interface that allows rapid coding of new simulation geometries and efficient visual validation of these geometries through an integrated geometry viewer. The drawback of using DOSRZnrc is that it requires cylindrical symmetry. In the case of modelling ion chambers, where predominately the geometry is cylindrical, DOSRZnrc is a good choice. The model employed here has detailed modelling of the stem, chamber wall, and electrode, at a level of detail similar to that in the
blueprint models used with the EGSchamber in Muir and Rogers 2010 and in Wulff et al. 2008. The one simplification required is that the chamber end is flat rather than slightly rounded as shown in Figure 6.1.1 (a). The uncertainty from this simplification is discussed and included in the uncertainties in Section 6.8. The uncertainty in $k_Q$ from the flat end is expected to be better than 0.2%. Any small error in $k_Q$ that would arise from the flat end would be highly correlated between similar MV beam energies, and insignificant (< 0.1%) when comparing the ratio of $k_Q$ from different 6 MV beams.

As DOSRZnrc requires cylindrical symmetry, the linac phase space file was output in 5 cm depth of water in the BEAMnrc model, and was input in the DOSRZnrc model at 5 cm depth in water, as shown in Figure 6.1.1 (b). This avoids having a cylindrical water surface in the beam path. It is noted that this approach only works at depth and DOSRZnrc is not suitable to model ion chamber response at shallow depths. The air cavity was defined by a cylinder with a diameter of 7.35 mm and a reduced length of 8.02 mm to match the active volume in the modeled approximation of a flat chamber end with the active volume of the chamber with a rounded end. The graphite wall thickness was 0.5 mm. The relative $k_Q$ was calculated by scoring the dose deposited in the air cavity, then changing all materials in the DOSRZnrc input file to water, whilst maintaining the geometries and scoring volumes, and scoring the dose deposited in water in the same position and volume as the air cavity. The same phase space file was used for both the chamber simulation and the water phantom simulation, as shown schematically in Figures 6.1.1 (b) and (c). The selected MC transport parameters the same as those listed in Table 2.4.1 for the BEAMnrc source models. $2 \times 10^{10}$ primary histories were used, and no variance reduction was employed. Each model was run five times with different random number seeds, and the average dose and standard mean was calculated from the runs. A single simulation took 300 CPU hours to run and was run on 20 parallel processors of the VPAC supercomputer, taking approximately 15 hours to run in real time.
Figure 6.1.1 (a) Schematic of the model of NE2561 chamber compared to a photo of a NE2561, (b) shows DOSRZNRC model with chamber with the position of the phase space file input and (c) shows DOSRZNRC model with water only.
6.2 Response of NE2561 model to 6, 10, and 18 MV Elekta beams

To test the validity of the NE2561 model, the relative $k_Q$ was calculated using phase space files from models of the ARPANSA standard 6, 10, and 18 MV photon beams, and also the Varian matched 6 MV beam. The BEAMnrc source models of the 10 and 18 MV photon beams were commissioned in a similar manner to 6 MV as described in Section 2.5. The model commissioning data is presented in Appendices A and B for the 10 and 18 MV beams respectively. The change in $k_Q$ with energy was compared to the $k_Q$ curve from TRS-398 (Andreo et al 2001) and also to a compilation of experimental $k_Q$ from Boutillon et al 1994, Guerra et al 1995, Palmans et al 1999, Seuntjens et al 2000, Duane et al 2003, Stücki et al 2003, LNHB 2006, Krauss et al 2007 and McEwen 2010. This collation of data is similar to that in Aalbers et al. 2008. The response of NE2561 to $^{60}$Co was not modelled, so the modelled NE2561 response curve was scaled with the average $k_Q$ at $\text{TPR}_{20,10} = 0.681$ (standard ARPANSA 6 MV beam) from the UK National Physical Laboratory (NPL) calibrations of two ARPANSA NE2561 chambers (NPL 2010). Figure 6.2.1 shows $k_Q$ for a NE2561 chamber as calculated by the ARPANSA model, from TRS-398, and from experimental data. The ARPANSA model shows excellent agreement within 0.3 % to a weighted sigmoidal fit to all experimental data, weighted by the relative uncertainties, and agreement to within 0.4 % to a sigmoidal fit to TRS-398 data.

![Figure 6.2.1 $k_Q$ of modelled NE2561 chamber with ARPANSA Elekta beams compared to TRS-398 and a compilation of experimental $k_Q$. The uncertainties shown are from statistical uncertainty in the MC simulations only.](image-url)
The ARPANSA modelled data was also compared to recent modelled and measured data by Muir et al 2011 for NE2561 and NE2611 chambers (these two chamber types are almost identical). The comparison is shown in Table 6.2.1. The values from Muir have been interpolated to the ARPANSA energies with a linear fit between the two closest energies using TPR_{20,10}. Good agreement is seen.

### Table 6.2.1 Comparing the ARPANSA modeled data to measured and modeled data by Muir et al 2011.

<table>
<thead>
<tr>
<th>Nominal energy</th>
<th>TPR_{20,10}</th>
<th>%dd</th>
<th>Ratio of Lye k_Q to Muir k_Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NE2561</td>
<td>NE2611</td>
<td>Modelled</td>
</tr>
<tr>
<td>6</td>
<td>0.681</td>
<td>67.4</td>
<td>1.000</td>
</tr>
<tr>
<td>10</td>
<td>0.738</td>
<td>72.9</td>
<td>1.001</td>
</tr>
<tr>
<td>18</td>
<td>0.781</td>
<td>78.6</td>
<td>1.002</td>
</tr>
</tbody>
</table>

### 6.3 Response of NE2561 model to 6 MV Varian beam

The NE2561 model was run using the phase space file from the true Varian BEAMnrc model. The results are shown in Figure 6.3.1. Only statistical uncertainties from the modelling are shown as other uncertainties are assumed to be correlated as discussed in Section 6.8. The k_Q of the Varian is 0.4 % less than the k_Q of the matched ARPANSA beam, despite the closely matched PDDs shown in Figure 2(b). This difference is not overly large for a clinical setting, and well within the uncertainty of 1% prescribed to k_Q in TRS-398. It is also consistent with a difference of less than the 0.5 % expected from Andreo 2000a for two clinical beams. The 0.4 % difference is however significant in terms of primary standard calibrations, where it is comparable to the best standard uncertainty currently achievable in a chamber calibration (Key Comparison BIPM.RI(I)-K6/BIPM). The investigation of Muir and Rogers in 2010 did not see such a large variation for 6 MV with their spectra and chambers under investigation. This may be due to the fact that they used the beam quality specifier %dd(10)_x which is more effective at distinguishing between heavily and lightly filtered beams (Xiong and Rogers 2011).
Figure 6.3.1 $k_Q$ of modelled NE2561 chamber with Varian 6MV beam compared to Elekta beams.

### 6.4 Spectra of matched beams

The discrepancy between the Varian and matched Elekta beam can be better understood by considering the spectra of the two beams. The solid lines in Figure 6.4.1 show the photon spectra in air at 100 cm from the phase space files of the Varian and matched Elekta. For ease of comparison, the two curves have been normalised to 0.5 MeV. Despite the very similar PDDs the two spectra are clearly different. The two modelled PDDs and their local differences are shown in Figure 6.4.2. Beyond $d_{\text{max}}$ the two PDDs are indistinguishable. There is a slight difference of less than 3% in the build-up area.
Figure 6.4.1 Spectra of Varian beam, matched Elekta beam, and Varian beam with Elekta target.

Figure 6.4.2 Modelled PDD of Varian beam and matched Elekta beam.

Considering the components in the beam path, the main difference between the two accelerators is the thickness of the targets. The Elekta has a thicker target and higher filtration,
and therefore requires a lower incident electron energy to achieve the same PDD as the Varian (6.1 MeV for the Varian, 5.9 MeV for the matched Elekta). This is analogous to kilovoltage beams which are specified by both their kV and half value layer (HVL). A single beam quality index of HVL by itself is not sufficient to define the kilovoltage beam, as a hard 50 kV and soft 100 kV with the same HVL will have very different spectra and consequently different chamber calibration factors. The chamber response to clinical megavoltage beams has a far smaller dependence on spectra compared to kilovoltage beams. With Megavoltage beams it is sufficient to use the single TPR\(_{20,10}\) beam quality index for clinical beams for an accuracy in \(k_Q\) of better than 0.5 % (Andreo 2000b). If an accuracy of 0.1 % was desired a second beam quality index may be necessary. Unfortunately with megavoltage beams the incident electron energy is usually not known, making it impractical to use the incident electron energy as a second beam quality index.

The Varian beam was remodelled with a modified target with extra Copper to mimic the Elekta target, and with a lower incident electron energy of 5.9 MeV. The resulting spectrum is shown by the dashed line in Figure 6.4.1. The new spectrum follows the Elekta spectrum extremely well, confirming that it is indeed the difference in the targets causing the spectral difference between the Varian and matched Elekta beam.

6.5 Response of NE2561 model to Elekta and Varian beams with matched targets

The NE2561 model was rerun with the phase space file from the remodelled Varian beam with extra Copper in the target. This particular simulation helps to distinguish whether the 0.4% difference between the Varian and matched Elekta is indeed due to the difference in spectra between the two beams or to some other difference between the two models. The results are shown in Figure 6.5.1, with the remodelled Varian beam shown by the open triangle. The \(k_Q\) of the remodelled Varian has shifted up to agree with the matched Elekta beam within the uncertainty of the simulations.

The NE2561 model was also rerun with a phase space file from a remodelled Elekta beam with less Copper in the target, and a higher incident electron energy of 6.1 MeV. The \(k_Q\) of this beam is shown in Figure 6.5.1 by the closed triangle. As expected, the \(k_Q\) of the remodelled Elekta is shifted down to agree the standard Varian beam within the uncertainty of the simulations. These
MC evaluation of the dosimetric uncertainty in matched 6 MV Elekta and Varian linacs

Simulations show that the spectral difference seen in Figure 6.4.1 causes a difference in $k_Q$ of around 0.3-0.4 %, and that a matched PDD will not distinguish this difference.

![Graph](image)

**Figure 6.5.1** $k_Q$ of modelled NE2561 chamber with ARPANSA Elekta beams, Varian beam, Varian beam with extra Cu in the target, and Elekta beam with less Cu in the target.

### 6.6 Designing a custom flattening filter to match Varian Spectrum

Ideally the Australian primary standard reference linac would have a Varian matched beam that matched not only with PDD, but also with spectra. The 6 MV Elekta has more filtration than a Varian beam due to the thicker target, so additional filtration cannot be simply added to match the spectra, and the target cannot be changed with an Elekta machine. However the flattening filter in the ARPANSA linac is physically accessible and a custom flattening filter can be designed with reduced thickness to compensate for the different target thickness.

Figure 6.6.1 shows the key components in designing the custom flattening filter. Each accelerator has filtration from the target, the flattening filter, and other components in the beam path. The central axis transmission was calculated for each accelerator using a narrow beam.
approximation and the incident electron energy. The thickness of the custom flattening filter was proportionally reduced until the central axis transmission roughly matched that of the Varian. The thickness was then finely adjusted until the spectra of the two accelerators matched as shown in Figure 6.6.2. The central axis beam flatness over the dimensions of the NE2561 at 10 cm depth was better than 0.1 %.

Figure 6.6.3 shows the results of the NE2561 model when run with the phase space file from the Elekta linac with a custom flattening filter. The $k_Q$ with the custom flattening filter agrees very well with the $k_Q$ from the true Varian, as expected from their well matched spectra. This result supports the idea that designing and building a custom flattening filter for the ARPANSA Elekta linac could produce a 6 MV beam that reproduces the response of a Varian beam for central-axis primary standard calibrations.

![Figure 6.6.1 Process for compensating for target differences with custom flattening filter](image-url)
Figure 6.6.2 Spectra of Varian beam, matched Elekta beam, and Elekta beam with custom flattening filter.

Figure 6.6.3 $k_Q$ of modelled NE2561 chamber with Elekta beam with custom flattening filter compared to ARPANSA Elekta beams and Varian 6 MV beam.
6.7 Investigating the flattening filter free (FFF) modality

The flattening filter of a medical linear accelerator is used to shape the fluence profile of the photon beam to produce a large flat beam profile up to field sizes of 40 cm$^2$, at the cost of reducing the dose rate by up to five times. It also modifies the photon spectra, increases the scattered radiation, dose out of field, beam penumbra, neutron contamination, and reduces the electron contamination (Vassiliev et al. (2006), Ponisch et al. (2006), Zhu et al. (2006), Cashmore (2008), Stathakis et al. (2008)). A large flat beam is redundant for many advanced radiotherapy treatments, such as IMRT. IMRT uses multiple small “beamlets” to produce highly conformal treatment plans with increased dose to the tumour and reduced dose to the normal tissue, and the optimization of these beamlets is not dependant on a large flat beam starting point. IMRT requires longer treatment times, in particular the new high dose hypo fractionated treatments and treatments that gate the beam to a single phase of the breathing cycle. These advanced treatments are driving the need for increased dose rate from medical linear accelerators to avoid prohibitively long treatment times. Operation without a flattening filter is becoming an increasingly attractive proposition.

Varian has recently released an accelerator with an FFF modality. An important question to address is how to calibrate these beams. As a first step in answering this question the flattening filter was removed from the models of both the Varian and the Varian-matched Elekta accelerator. The incident electron energy was increased in the FFF models until the TPR$_{20,10}$ reached 0.671 (the beam quality of the 6 MV Varian beam). The electron energy was increased to 8.2 and 8.7 MeV for the Elekta FFF and Varian FFF models respectively. Figure 6.7.1 shows the photon spectra in air at 100 cm from the phase space files of the Varian FFF and Elekta FFF, compared to the spectra of the Varian-matched Elekta beam. All curves have been normalised to 0.5 MeV. The two FFF spectra are manifestly different from the ARPANSA Elekta beam with the Flattening filter.
Figure 6.7.1 Spectra of the FFF Elekta beam and FFF Varian beam compared to ARPANSA Varian-matched Elekta beam with the same TPR\textsubscript{20,10}.

The NE2561 model was run with phase space files from the Varian and Elekta FFF models. The resulting $k_Q$ for the FFF beams are shown in Figure 6.7.2. Both FFF beams have a $k_Q$ shifted down from the ARPANSA 0.671TPR\textsubscript{20,10} 6 MV beam. The $k_Q$ for the Elekta FFF beam is 0.6 % less than the ARPANSA Elekta beam, and the $k_Q$ for the Varian FFF beam is 0.8 % less.

This result is not surprising. Xiong and Rogers in 2008 compared stopping power ratios of beams with and without flattening filters and found that the lightly filtered beams consistently had a lower stopping power ratio than the heavily filtered beams with the same TPR\textsubscript{20,10}, with a difference ranging from 0.4-1.0 %. Using %dd(10)\textsubscript{x} as a beam quality specifier resulted in far more consistent stopping power ratios between the heavily and lightly filtered beams. The problem with TPR\textsubscript{20,10} not distinguishing between heavily and lightly filtered beams is a known problem and was noted by Rosser \textit{et al} in 1994.

A discrepancy of 0.8 % is potentially of clinical concern, and suggests that simply using the TPR\textsubscript{20,10} of a FFF beam to interpolate a calibration factor from the ARPANSA primary standard measurements will result in significant dosimetric error. It is encouraging that the Elekta and Varian FFF beams show reasonably close agreement. The ARPANSA linac has the potential for
MC evaluation of the dosimetric uncertainty in matched 6 MV Elekta and Varian linacs

a FFF beam, and creating a primary standard Elekta FFF beam may be the best approach for calibrating all FFF beams in the future.

Although simply removing the flattening filter from the existing linac models and modelling the NE2561 response gives a good first indication of the possible magnitude of dosimetric errors in calibrating FFF beams, exact manufacturers specification of actual FFF beams should be included in future models, as well as investigating different photon energies, and different chambers such as the NE2571 farmer chamber.

![Figure 6.7.2](image)

**Figure 6.7.2** $k_Q$ of modelled NE2561 chamber with FFF Elekta beam and FFF Varian beam compared to ARPANSA Elekta beams.

### 6.8 Uncertainties

The uncertainty in the modelled determination of $k_Q$ is composed of the statistical uncertainty in the Monte Carlo simulations and systematic uncertainties from stopping power ratios, EGSnrc transport, chamber geometry and averaging over a dose volume rather than calculating a point dose. It is assumed uncertainties in the photon cross-sections are correlated and that the uncertainty in $k_Q$ is negligible.
The uncertainty in the stopping power ratios is taken from the investigation by Muir and Rogers 2010, using the results for chamber type with a graphite wall and aluminium electrode. Uncertainty in the EGSnrc electron transport code has been shown to be accurate to within 0.1 % with respect to its own cross-sections for ion chamber response simulations (Kawrakow 2000b). Uncertainty in the chamber geometry has been divided into uncertainty in the thickness of the chamber wall and uncertainty due to the geometry approximation required for the cylindrical symmetry of DOSRZnrc. Muir and Rogers 2010 investigated both of these effects. For a wall thickness variation of 5 % in a range of chamber types, the worst-case corresponding change in \( k_Q \) was 0.1 %. The Exradin A12 chamber was modelled using exact blue-print specifications, with simplified stem, and with no stem and a purely cylindrical geometry. A spread of 0.2 % was noted for the three variations. An uncertainty of 0.2 % was assumed for the simplified geometry assumptions in this work. It is assumed that \( W/e \) is independent of energy across the range of beams investigated, which is an approximation. Following TRS-398, an uncertainty in \( k_Q \) of 0.5 % is assigned for this component. Dose is calculated by averaging over the chamber volume, rather than calculating a point dose. Uncertainty in this component was estimated using an exponential fit to the PDD data from 5 – 15 cm. The difference in dose calculated from the fit averaged over the chamber diameter compared to the point dose at 10 cm was found to be less than 0.01 %.

The combined uncertainty is 0.59 % in the determination of \( k_Q \) from the model of the NE2561 chamber. However the primary focus of this paper is not to determine the response of \( k_Q \) over a range of energies, but rather to compare two \( k_Q \) from clinical beams with the same TPR\(_{20,10}\) but slightly different spectra. In this case it is expected that uncertainties in the stopping power ratios, EGSnrc, chamber geometry, \( W/e \), and dose averaged over a volume will be highly correlated. It is assumed that any uncorrelated components due to the different spectra will lead to negligible change in \( k_Q \) and that the uncertainty in a ratio of \( k_Q \) with the same TPR\(_{20,10}\) is dominated by statistical uncertainty.
Table 6.8.1 Relative standard uncertainties in the modelled determination of $k_Q$ for a NE2561 chamber

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>relative standard uncertainty</th>
<th>100 $u_A$</th>
<th>100 $u_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping power ratios</td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>EGSnrc</td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Wall thickness</td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Cavity geometry</td>
<td></td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>$W/e$</td>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>Dose to volume</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td></td>
<td></td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Uncertainty in $k_Q$**

| quadratic summation                    | 0.08                          | 0.59      |
| combined relative standard uncertainty |                               | 0.60      |

**Uncertainty in ratio of $k_Q$ with same TPR$_{20,10}$**

| quadratic summation                    | 0.08                          |           |
| combined relative standard uncertainty |                               | 0.08      |
Chapter 7  Conclusions

The Australian medical reference linac is an Elekta Synergy platform linac, but includes an additional 6 MV beam that is TPR$_{20,10}$ matched to a Varian linac. The Monte-Carlo investigation of the $k_Q$ of a secondary standard NE2561 chamber has shown a difference of 0.4 % between a 6 MV Varian and the matched 6 MV Elekta accelerators. This difference is not large but is significant for primary standard calibrations, and the difference may well be larger for other chambers or for higher photon energies. There are three approaches ARPANSA could take to deal with the discrepancy in calibration factors caused by using the Elekta Synergy Platform linac to calibrate chambers intended for use with a linac from a different manufacturer. The 0.4 % could simply be included in the uncertainty budget. Alternatively, a correction factor could be applied if the modelling was extended to cover commonly used chambers and a range of energies. A final option would be to use a custom flattening filter that matches not only the Varian PDD, but also the spectra. To better inform ourselves on the best approach this work needs to be extended to other chambers, in particular the NE2571, other energies, such as 18 MV, and other manufacturers to complete the picture. It is worth noting that this problem exists when using chambers calibrated in Cobalt-60 for linac calibrations, and is included in the 1% uncertainty factor assigned to $k_Q$ in TRS-398.

The Monte-Carlo investigation of the $k_Q$ of a secondary standard NE2561 chamber was extended to consider the response with flattening filter free beams. The $k_Q$ from a modelled Varian FFF beam showed a difference of 0.8 % compared to the 6 MV Elekta with the same TPR$_{20,10}$, and the Elekta FFF beam showed a difference of 0.6 %. This demonstrates that TPR$_{20,10}$ alone is not sufficient as a beam quality specifier for FFF beams, however TPR$_{20,10}$ could be used together with a dedicated FFF beam on the ARPANSA reference linac. Further investigations of other chambers and other energies would be useful in establishing the range of uncertainties in primary standard calibrations of FFF beams.

A new method was developed to convert absorbed dose to graphite to absorbed dose to water to remove the influence of the spectrum from the primary standard graphite calorimetry measurements. The new method uses a direct Monte Carlo conversion of the dose to the calorimeter core to absorbed dose to water at the reference depth of the ionization chamber. Careful commissioning of the Monte Carlo model of the 6 MV source against water tank measurements and both water and graphite phantom PDDs gives confidence in the chosen
transport parameters, geometries, and mass–energy absorption coefficients of the model. Comparison to NPL calibration factors of NE2561 chambers gave good agreement of 0.1 %.

References to commercial products are provided for identification purposes only and constitute neither endorsement nor representation that the item identified is the best available for the stated purpose. Some details regarding specifications used in the modelling are omitted to comply with non-disclosure agreements with the manufacturers.
Appendix A. Commissioning the Elekta model, 10 MV Handbag D

The model of the ARPANSA 10 MV beam was commissioned against water tank measurements using the methodology explained in Chapters three and four. The best agreement was found with an incident mean electron energy of 10.1 MeV for the standard Elekta 10MV model. The model used a 0.5 mm FWHM source size and a Gaussian spectrum source with 0.5 MeV FWHM spread. Comparison of measured and simulated profiles and PDDs of the 10 x 10 cm field and 30 x 30 cm field are included below.

![Graph of measured vs simulated dose profiles](image)

**Figure A.1** Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 2.1 cm. The inset shows the global difference between the measured and simulated values (+/- 2 % is shown by the dashed red lines).
**Figure A.2** Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global difference.

**Figure A.3** Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure A.4 Comparing measured and simulated 10 x 10 cm PDDs from the Elekta 10 MV beam. The inset shows the local difference.

Figure A.5 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 2.1 cm. The inset shows the global difference.
Figure A.6 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global difference.

Figure A.7 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 10 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.
Figure A.8 Comparing measured and simulated 30 x 30 cm PDDs from the Elekta 10 MV beam. The inset shows the local difference.

Appendix B. Commissioning the Elekta model, 18 MV Handbag D

The model of the ARPANSA 18 MV beam was commissioned against water tank measurements using the methodology explained in Chapters three and four. The best agreement was found with an incident mean electron energy of 15.5 MeV for the standard Elekta 10MV model. The model used a 0.5 mm FWHM source size and a Gaussian spectrum source with 0.5 MeV FWHM spread. Comparison of measured and simulated profiles and PDDs of the 10 x 10 cm field and 30 x 30 cm field are included below.
Figure B.1 Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 2.1 cm. The inset shows the global difference.

Figure B.2 Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global difference.
Figure B.3 Comparing measured and simulated 10 x 10 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.

Figure B.4 Comparing measured and simulated 10 x 10 cm PDDs from the Elekta 18 MV beam. The inset shows the local difference.
Figure B.5 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 2.1 cm. The inset shows the global difference.

Figure B.6 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 10 cm. The inset shows the global difference.
Figure B.7 Comparing measured and simulated 30 x 30 cm dose profiles from the Elekta 18 MV beam incident on a water phantom at a depth of 20 cm. The inset shows the global difference.

Figure B.8 Comparing measured and simulated 30 x 30 cm PDDs from the Elekta 18 MV beam. The inset shows the local difference.
Chapter 9  References


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