Modelling the use of solid state detectors to determine seed locations in low dose rate brachytherapy

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Dean Cutajar

1st September 2003
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Abstract

Brachytherapy involves the treatment of cancer through the implantation of radioactive seeds into the tumour. A high dose of radiation is given to the tumour while healthy tissue surrounding the tumour receives only a small dose. By implanting multiple seeds into the tumour at selected locations, the necessary dose may be given to the tumour covering the entire geometry of the tumour. If the placement of the seeds within the tumour is inaccurate, the dose distribution within the tumour will be affected. The tumour may receive a smaller than required dose, or the healthy tissue surrounding the tumour may receive an excessive dose. The positioning of the seeds within the tumour needs to be monitored in real time during insertion in order to make corrections for misplaced seeds. The following thesis presents a detailed account of experiments conducted at the Centre for Medical Radiation Physics, University of Wollongong. The goal of these experiments was to conduct Monte Carlo simulations of brachytherapy seeds in water to study how certain characteristics of the radiation distribution, arising from these seeds, vary at different positions in water around the seeds. An outcome of this was to perceive a need to develop a system to determine the location of brachytherapy seeds within the body using measured characteristics of the radiation distribution as determined using solid state detectors. The code used for the Monte Carlo simulations was Egsnrc V2 (Electron Gamma Shower 4, modified by the National Research Council of Canada). The user subroutines used were Dosrznrc, to estimate the dose distribution around the seeds, and Flurznrc, to estimate the radiation spectrum distribution around the seeds. The seeds studied were OncoSeed number 6711 from
Amersham Health, which are low energy photon emitters whose active source is Iodine 125.

The dose distribution in water around the 6711 seeds was shown to vary as a function of distance from the seed. An attempt was made to find a relationship between the distance from the source and the measured dose using the attenuation coefficient. This was unsuccessful as it was shown that the average attenuation coefficient varies with distance from the source due to the radiation consisting of different energy photons, which are attenuated at different rates. A distance dependent attenuation coefficient was not used to overcome this as the dose distribution varied as a function of angle around the seed as well due to the varying thickness of titanium shell encapsulating the source. Hence, a varying attenuation coefficient would be a function of both distance from the seed and angle about the seed. The main interaction resulting in energy loss for photons in water is the photoelectric effect, in which the medium absorbs all of the energy of the interacting photons. This indicates that the location of peaks in the photon spectrum should be constant with distance from the source. only the intensities of peaks should be attenuated. Since different energy photons are attenuated by different amounts when passing through matter, different energy peaks in the photon spectrum should be attenuated by different amounts. This was shown to be true. Using this principle a relationship between the ratio of peaks in the spectrum and distance from the source was found. By measuring the spectrum from a brachytherapy seed using a solid-state detector in spectroscopy mode, and comparing the peak heights in the spectrum, the distance from the seed to the detector may be determined. By repeating this analysis for measurements
from at least 3 different positions around the desired area the location of the brachytherapy seed may be determined. This method would only be effective if the ratio of peaks in the spectrum was constant with changes in angle around the seed. This was found to not be the case. The peak ratios were found to vary as a function of both distance from the seed and angle around the seed. A formula was devised to determine both the distance to the seed and the angle of measurement to the seed by comparing the peak heights of three peaks in the spectrum.

Experimental measurements were conducted using a 6711 seed in a Perspex phantom. The experimental values were not consistent with the calculated values, as low energy photons are not attenuated by the same rates in Perspex as they are in water. The experimental values did, however, show that the peak ratios of the measured spectra vary as a function of distance to the source. This work presents a generic approach to the development of a system to locate brachytherapy seeds using detectors in spectroscopy mode, as well as the development of a dose planning system.
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Chapter 1

Introduction

1.1 Brachytherapy

In 1912 it was discovered that radioactive substances placed on the pelvis could cure uterine cancer [1]. With this scientific break-through brachytherapy was born in the form of contact therapy. Contact therapy encapsulates any form of treatment where the source of radiation is placed externally in contact with the skin. Brachytherapy has since been generalized to cover radiotherapy of a tumour, where the source of radiation has been placed inside the tumour through the insertion of an implant [2] in the form of a brachytherapy seed.

Figure 1.1. A two dimensional representation of a brachytherapy seed, located in the center of a tumour
Brachytherapy, from the Greek word brachys, meaning short, is the term given to the treatment of cancer where the source of radiation is close to the tumour. As opposed to teletherapy (teles being the Greek word for far away) where the source of radiation is at a great distance to the tumour, resulting in a close to uniform irradiation to the tumour, brachytherapy sources produce non-uniform doses. This is the main advantage of brachytherapy. A source may be placed inside a tumour, delivering a large dose to the tumour, whilst delivering only a small dose to the surrounding tissue. Brachytherapy may also be used in conjunction with teletherapy, where teletherapy is used initially to cover a large area, and brachytherapy is used finally to deliver a large dose to the tumour core. Brachytherapy has other advantages over teletherapy including shorter treatment times and less expensive equipment [2].

There are two main types of implants used in brachytherapy, removable and permanent implants. Removable implants are placed inside the body for short periods of time, from a few seconds up to a few days at a time. Permanent implants are left inside the body. Permanent implants pose no danger to others as most of the radiation is absorbed inside the body, and the half-life of the radioactive source is usually short. Removable implants use sources with greater dose rates. They are finally removed for safety reasons [2].

\(^{125}\)I and \(^{103}\)Pd radioactive isotopes are commonly used as the source of radiation within low dose rate brachytherapy seeds. Prostate brachytherapy treatment usually requires implanting at least fifty seeds in pre-determined locations within the tumour. These
locations are calculated to give a relatively even, but effective, dose throughout the volume of the tumour.

![Diagram of several brachytherapy seeds spread within a tumour](image)

**Figure 1.2. Several brachytherapy seeds, spread within a tumour, to give a relatively even dose of radiation throughout the tumour**

Brachytherapy is used extensively to treat prostate cancer. A uniform distribution of seeds within the prostate will give an adequate dose distribution throughout, but can irradiate the urethra to intolerably high levels [3]. Task group 56 recommends that peripheral loading be used rather than uniform loading to spare the urethra. Wayne M. Butler, et al [3], recommend a modified uniform loading to deliver a more homogenous dose distribution whilst delivering a low dose to the urethra. Brachytherapy treatment of the prostate began with open implant techniques, where the gland would be surgically exposed and the seeds inserted freehand. This method achieved an 87% success rate [4].
Injections of $^{125}$I isotopes have only achieved a 70% success rate. Poor patient selection and erratic seed placement are blamed for this lower success rate [4].

To determine the required locations of the seeds to be implanted, images of the tumour and surrounding areas are taken using trans-rectal ultrasound or computer tomography (CT) scans. Once the desired seed locations are calculated, the seeds are implanted using guiding needles. A needle spacing template is used to correctly position the needle upon entry to the skin. It is important that all guiding needles be inserted in parallel to each other in order to place the seeds in the correct locations. In practice, needles may diverge from their required directions as they penetrate different layers of the body such as the skin or prostate, resulting in the seeds being placed in the wrong places [5]. Other factors that may contribute to seeds not being placed in their planned locations are gland motion, swelling and bleeding [6]. Peter L. Roberson, et al [7], studied the errors of seed positioning using ultrasound and fluoroscopic-guided permanent $^{125}$I implants. They established that source placement precision is the limiting factor in delivering the appropriate dose distribution.

A seed placed in the wrong location can result in a combination of two unwanted outcomes. Parts of the tumour may not receive the required dose or healthy tissue may receive an unnecessarily high dose. There is a need for a real time monitoring system of seed implantation to be developed. With real time monitoring of seed locations during insertion, any errant seeds may be compensated for through the recalculation of desired seed locations for the remaining seeds. A monitoring system would require an array of
photon sensitive radiation detectors to be placed around the treatment volume. To determine the location of a seed, the dose may be measured at each detector, giving an estimation of the distance from each detector to the seed. An estimate of the source location within the treatment volume will be obtained. This is not an easy procedure as there are complicating factors such as attenuation within the tumour and a variation of dose distribution due to the source shape. To mathematically specify the dose distribution around a brachytherapy source the Task Group 43 (TG43) protocol was created.
Chapter 2

Literature Review

2.1 Dose Simulation From A Brachytherapy Source

2.1.1 The interaction of low energy photons with matter

Electromagnetic radiation may interact with matter through many individual processes. If it is assumed that the interactions between photons and matter are single processes associated with individual atoms then these individual processes may be characterised by an interaction cross-section, $\sigma$. $\sigma$ may be split into constituents of partial cross-sections.

$$\sigma = \sigma_a + \sigma_b \ [8]$$

where $\sigma_a$ refers to the cross-section of processes where energy is absorbed and $\sigma_b$ refers to the cross-section of processes where energy is scattered. For a beam of intensity $I$, if the attenuation of the beam through a medium is proportional to the beam intensity and medium interaction cross-section then

$$-\Delta I = I\sigma n\Delta x \ [8]$$

where $n$ is the number of atoms per unit volume, $\sigma$ is the removal cross-section per atom and $x$ is the depth of the beam through the medium. This becomes

$$I = I_0 e^{-\sigma nx} \ [8]$$
The three main interactions between low energy photons and matter are the photoelectric effect, the Compton effect and Rayleigh scattering.

**The Photoelectric Effect**

The photoelectric effect is the most important interaction for photons, with energies between 1 and 100 keV in water, in terms of energy absorption. The photoelectric effect involves the total absorption of an incident photon by an electron that is bound to an atom in the absorbing medium. For photoelectric absorption to take place, the energy of the incident photon must be greater than the binding energy of the released electron. Photoelectric absorption occurs most readily when the photon energy is close to the binding energy of the electron. The inner electrons contribute the most to the photoelectric effect, with the K shell electrons having the greatest contribution, then the L shell electrons and so on. If the energies of the incident photons are less than the binding energy of the K shell electrons, the L shell electrons will be the greatest contributors. For an increase in energy, there is a decrease in probability that a bound electron will resonate with the incident photon. Hence, an increase in energy will generally result in a decrease in photoelectric interaction cross-section.
The Compton Effect (incoherent scattering)

The Compton effect occurs when a photon is incident on an electron and deflected through an angle. The scattered photon loses some of its energy to the electron. The amount of energy lost depends on the initial energy and the angle of deflection. During Compton interactions energy and momentum are conserved. For photons with energies between 1 and 100 keV in water, the Compton effect provides a significant number of interactions but little energy loss per interaction.

For a photon of energy \( h\nu \) incident on a free, unbound electron, if the final energy of the photon is \( h\nu' \) and the scattering angle of the photon is \( \theta \)

![Figure 2.1 The Compton effect.](image)

Using conservation of energy and momentum gives

\[
  h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2} (1 - \cos \theta)} \quad [8]
\]
Thompson and Rayleigh Scattering (Coherent Scattering)

Thompson and Rayleigh scattering are interactions of photons with matter that result in virtually no energy loss for the scattered photons. Although these interactions result in no energy loss they still contribute to the total interaction cross-section.

Thompson scattering occurs when a photon is incident on an electron. The photon applies a periodic force on the electron, causing it to oscillate at the forcing frequency. The electron returns to a stable state by radiating a photon, the direction of which is dependent on the orientation of the electron as an electric dipole. This process appears as the scattering of a photon with no energy loss.

Rayleigh scattering occurs when the effects of Thompson scattering are shared amongst all of the electrons in an atom rather than a single electron. The vibrations of all the electrons are in phase and give rise to the emission of a single photon when returning to a stable state.
2.1.2 Task Group 43 Protocol

In 1998, the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) formed Task Group 43 (TG43). The goal of TG43 was to review recent publications involving the dosimetry of interstitial brachytherapy sources and to recommend a new protocol to use for this dosimetry. This protocol would include a new method for specifying dose distributions, and data sets for required dosimetry parameters. This was necessitated by the release of several articles introducing revised standards for calibration, source strength quantities and formalisms and dose calculation. These articles also introduced new dosimetry data, including radial dose functions, dose rate constants and anisotropy functions for various sources. With the introduction of these formalisms and data sets, it was necessary to introduce a protocol, stating which formalisms and data sets to use, that would satisfy the needs of the medical physics community. The result of the TG43 review is a formalism clearly defining the physical quantities and functions required for the calculation of dose from a single linear source. This formalism is based on measurable quantities and decouples interrelated quantities into separate functions. Calculations based on this protocol have resulted in dose rate changes up to 17% relative to the point source approximation, which is given by the one dimensional formula

\[
D(r) = A_{\text{app}} f_{\text{med}} (\Gamma_\delta) \chi \left(1/r^2\right) T(r) \phi_{\text{an}} \quad [9]
\]

where \(D(r)\) is the dose rate at a distance \(r\) from the source, \(A_{\text{app}}\) is the apparent activity, \(f_{\text{med}}\) is the exposure to dose conversion factor, \((\Gamma_\delta)\chi\) is the exposure rate constant for the radionuclide within the source, \(T(r)\) is the tissue attenuation factor and \(\phi_{\text{an}}\) is the anisotropy constant. This approximation becomes inaccurate for calculations near the source. The source size, shape and structure need to be considered for dose rate
calculations close to the source. The point source approximation is also based on photon fluence in free space calculations. This approximation becomes inaccurate for non point sources in a scattering medium. The TG43 protocol takes into account the source size, shape and structure, as well as scattering within the medium. For a two dimensional representation of the source, the TG43 protocol dose rate is

\[ D(r, \theta) = S_k \Lambda \left[ \frac{G(r, \theta)}{G(r_0, \theta_0)} \right] g(r) F(r, \theta) \]  

Where \( S_k \) is the air kerma strength of the source, \( \Lambda \) is the dose rate constant, \( G(r, \theta) \) is the geometry factor, \( g(r) \) is the radial dose function and \( F(r, \theta) \) is the anisotropy function. \( G(r_0, \theta_0) \) is the geometry factor at a fixed reference point \( (r_0, \theta_0) \). The reference point is chosen to be 1 cm from the centre of the source, on the transverse bisector, such that \( (r_0, \theta_0) = (1, \pi/2) \).

Figure 2.2. Two dimensional representation of a brachytherapy seed.
Air Kerma Strength, $S_k$

The Air kerma strength, $S_k$, is a measure of the source strength and is analogous to the apparent activity, $A_{app}$, in the point source approximation. The air kerma strength is defined to be the air kerma rate in free space ($K(r)$) when measured on the transverse axis of the source ($\theta=\pi/2$), multiplied by the square of the distance to the centre of the source ($r^2$).

$$S_k = K(r) r^2 \quad [9]$$

When determining the air kerma strength, $K(r)$ must be measured at a large distance from the source, such that the source appears as a point source. The air kerma strength is specified in terms of a reference point, $r_0$, which is usually 1m. One air kerma strength unit is defined to be equivalent to the units of $\mu$Gy m$^2$ h$^{-1}$.

Dose Rate Constant, $\Lambda$

The dose rate constant, $\Lambda$, is defined to be the dose rate at a point 1cm from the source on the transverse axis, for a source of one air kerma unit strength in water. The dose rate constant is defined to be an absolute quantity, and is the only non-normalised quantity in the TG43 dose rate function. In terms of the dose rate and the air kerma strength, the dose rate constant, $\Lambda$, may be represented as

$$\Lambda = D(r_0,\theta_0) / S_k \quad [9]$$

The dose rate constant is equivalent to the exposure rate constant in the point source approximation.
**Geometry Factor, G(r,θ)**

The geometry factor is the function that accounts for the source not being a point source. Only the special distribution of the radionuclide within the source is accounted for in the geometry factor. The geometry factor is defined as

\[
G(r,\theta) = \frac{\int_V [\rho(r')dV'/(r'-r)^2]}{\int_V \rho(r')dV'}
\]  

[9]

Where \( \rho(r') \) is the density of radioactivity at a point \( p(r') \) within the source. The integration is over the volume of the source, \( V \). Since the distribution of radiation within the source is sometimes unknown or difficult to obtain, it is often necessary to use an approximation for the geometry factor. For a point source, the geometry factor reduces to \( G(r) = r^{-2} \). If the source is approximated to be a line source, the geometry factor reduces to \( G(r) = \beta/( L r \sin \theta ) \) [10]. Where \( L \) is the length of the active volume of the source and \( \beta \) is the angle subtended by both ends of the source to the point of measurement, \( (r,\theta) \).

*Figure 2.3. Geometry of brachytherapy seed in the line source approximation*
**Radial Dose Function, \( g(r) \)**

The radial dose function accounts for the absorption and scattering of radiation within the medium. The radial dose function is specified along the transverse axis. The radial dose function is analogous to the tissue attenuation factor in the point source approximation. The radial dose function is defined as

\[
g(r) = \left( \frac{D(r, \theta_0) G(r_0, \theta_0)}{D(r_0, \theta_0) G(r, \theta_0)} \right) \tag{9}
\]

The radial dose function may be approximated by

\[
g(r) = C_1 e^{-\mu_1 r} + C_2 e^{-\mu_2 r} \tag{11}
\]

where the first term accounts for attenuation within the medium and the second term accounts for the initial build up. \( g(r) \) reduces to zero at large distances.

**Anisotropy Function, \( F(r, \theta) \)**

The anisotropy function accounts for the angular variation in dose distribution around the source due to absorption and scattering in the medium and source encasing. The anisotropy function is defined as

\[
F(r, \theta) = \left( \frac{D(r, \theta) G(r, \theta_0)}{D(r, \theta_0) G(r, \theta)} \right) \tag{9}
\]

The anisotropy function is analogous to the anisotropy constant in the point source approximation.
2.1.3 Low dose rate seed construction

The source studied was the OncoSeed number 6711 from Amersham Health Pty Limited, unit 4, 2 Eden Park drive North Ryde, NSW 2113, Australia. This seed consists of radioactive Iodine 125, absorbed onto a silver rod, encapsulated in a hollow titanium cylinder with welded ends. The following cross-sectional dimensions were obtained from the OncoSeed 6711 technical data sheet.

![Source Construction Diagram]

Figure 2.4. Source geometry from OncoSeed 6711 technical data sheet.

$^{125}\text{I}$ decays by electron capture and has a half-life of 59.43 days [12]. The electron capture within the Iodine results in the emission of multiple photons and electrons. The following table summarises the emissions from the Iodine.
### $^{125}$I Decay Table, Decay Mode Electron Capture

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Energy (keV)</th>
<th>Mean number/disintegration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>35.4</td>
<td>0.0666</td>
</tr>
<tr>
<td>K Internal Conversion Electron</td>
<td>3.6</td>
<td>0.8</td>
</tr>
<tr>
<td>L Internal Conversion Electron</td>
<td>30.9</td>
<td>0.1142</td>
</tr>
<tr>
<td>M Internal Conversion Electron</td>
<td>34.6</td>
<td>0.019</td>
</tr>
<tr>
<td>K Alpha-1 X-Ray</td>
<td>27.4</td>
<td>0.7615</td>
</tr>
<tr>
<td>K Alpha-2 X-Ray</td>
<td>27.2</td>
<td>0.3906</td>
</tr>
<tr>
<td>K Beta-1 X-Ray</td>
<td>30.9</td>
<td>0.2056</td>
</tr>
<tr>
<td>K Beta-2 X-Ray</td>
<td>31.8</td>
<td>0.0426</td>
</tr>
<tr>
<td>L X-Ray</td>
<td>3.7</td>
<td>0.2226</td>
</tr>
<tr>
<td>KLL Auger Electron</td>
<td>22.6</td>
<td>0.1416</td>
</tr>
<tr>
<td>KLX Auger Electron</td>
<td>26.4</td>
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<tr>
<td>KXY Auger Electron</td>
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</tr>
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<td>LMM Auger Electron</td>
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</tr>
<tr>
<td>MXY Auger Electron</td>
<td>0.8</td>
<td>3.6461</td>
</tr>
</tbody>
</table>

Figure 2.5. Data obtained from "Introduction to Radiological Physics and Radiation Dosimetry", Frank H Attix, John Wiley and Sons, 1986, Page 536.

The Iodine source within the seed is contained within a layer of titanium. The electrons emitted are absorbed in the titanium. The primary emissions from the seeds are photons with energies of 35.4 keV, 31.8 keV, 30.9 keV, 27.4 keV, 27.2 keV, and 3.7 keV. Photons with energies 22.1 keV and 25.2 keV are also present. These are fluorescent X-Rays, emitted by the silver within the seed [13].
2.2 Monte Carlo Simulation Of Doses

2.2.1 The structure of Monte Carlo simulation

Monte Carlo simulation involves the prediction of the effects of radiation in desired systems by examining the radiation on a particle by particle basis. Using computer calculations, the path of each particle is followed, from the point of origin to the point of absorption. Interactions between each particle and the surrounding media are simulated using pre-obtained cross-sectional data. The paths of any secondary particles emitted as a result of these interactions are also followed. Once all of the energy introduced into the system from the initial particle has been absorbed by, or escaped, the system, a map of the energy deposition throughout the system is created. This is repeated for a very large number of particles. The results for each simulated particle are averaged. The final result is an estimate of the average energy deposited in the system per particle due to the radiation source. The data that can be obtained for any location in the system includes dose deposited per particle, dose deposited per electron/photon, particle fluence, energy spectrum, photon spectrum and electron spectrum.
2.2.2 Egsnrc V2

Egsnrc V2 is version 2 of the National Research Council of Canada’s (NRC) modified code for Electron Gamma Shower 4 (Egs4). Egs4 is a Monte Carlo code, the structure of which is suitable for simulations in medical physics applications. Egs4, however, lacks the required accuracy at low photon energies. To overcome these inaccuracies, NRC modified the Egs4 code, resulting in Egsnrc. Egsnrc V2 was used for all of the following simulations. Egsnrc V3 was released in September, 2002, but did not include any modifications that would give different results than V2 for these low energy simulations [14].

Electron Gamma Shower

Released in 1985, Egs4 is a Monte Carlo code written in Fortran. Through Egs4, the radiation transport of electrons, positrons or photons can be simulated in any element, compound or mixture containing elements with element numbers between 1 and 100. Both photons and charged particles are transported at random. Egs4 can simulate the transport of photons with energies from 1 keV to several thousand GeV. Charged particles with energies from a few tens of keV to a few thousand GeV may also be transported [14].

Egs4 takes into account the following physics

- Bremsstrahlung radiation
- Positron annihilation
- Molière multiple scattering
- Moller ($e^+e^-$) and Bhabha ($e^+e^-$) scattering
- Continuous energy loss for charged particles between interactions
- Pair production
- Compton (incoherent) scattering
- Rayleigh (coherent) scattering
- Photoelectric effect

Since 1985, the following additions have been made
- Electromagnetic field transport
- ICRU 37 compliant stopping powers
- Improved photon cross-sections
- Photo electron angular distributions
- Low-energy electron cross-section modelling
- More accurate trigonometric functions
- Single elastic scattering
- Bound Compton scattering
- Doppler broadening and linearly-polarised photon scattering [14]

The EGS code contains two subroutines, Hatch and Shower, which may be called by the user. These subroutines call the other subroutines in the EGS code, which may call the user written codes, Howfar, Hownear and Ausgab. As well as the user written subroutines, the user must write a Main program. The user written codes may communicate with the EGS code through the use of common variables. Some examples
of common variables include medium information, radiation energies, energy limits and distance units [14].

The Main program performs the following operations in sequence.

- Initialises user written subroutines and common variables
- Calls the subroutine Hatch which “Hatches EGS”, initialising the material data from data files created by PEGS, a program that produces data files containing cross-sectional information for the media to be used in the simulation
- Calls the subroutine, Shower, initialising a cascade for a history or case. Once the cascade is completed, Main calls Shower to initialise another cascade. This is repeated until limits on the number of events are met.

Figure 2.6. The Egsnrc code system showing the order each subroutine is called [14].
Hatch initialises the material information, taking cross-sectional information from data files created by PEGS, assigning this cross-sectional information to specific regions in a three dimensional space. The locations of these regions are designed to match the geometry of the system to be simulated and are stipulated by the user in Main [14].

Shower is called by Main to initialise cascades. Main must pass certain variables to Shower to initialise a history. These variables tell Shower the type of initial particle as well as the initial energy, location, direction of travel and region of the particle. These variables are generated randomly using source distributions and energy spectra as described by the user [14].

Egs4 is a code that separates the physics and geometry calculations into separate subroutines. Howfar and Hownear are the subroutines that execute the geometry calculations. Howfar is called by Shower to calculate how far the particle will travel in the current medium before an interaction. Howfar uses the cross-sectional data and a random number generator to simulate how far the current particle will travel, and determines whether the particle will cross a boundary into another region. Hownear is a simple subroutine that returns only one value, the distance from the current position of the particle to the nearest region boundary [14].

Ausgab is the subroutine that scores the desired data for the simulation. After every interaction, Ausgab is called, and the data for each particle after the interaction is passed on to Ausgab, including particle type, position, energy and direction of travel. Since
Ausgab is a user programmed subroutine, the user determines the energy cut-offs to stop transporting the secondary particles. Ausgab is programmed by the user to score desired information from the interaction data passed to it [14].
2.2.3 Dosrznrc

Dosrznrc is a code written by NRC which simulates a photon or electron source in an arbitrary volume. The purpose of Dosrznrc is to score the energy deposited (or dose) in specific regions around a source. The geometry of the system containing the source and surrounding media is specified in right cylindrical geometry (RZ geometry, cylindrical coordinates). Dosrznrc initialises the user variables through the use of an input file. This input file allows the user to set variables in the Main program. The input file accomplishes several tasks [15].

- Defines the geometry of the source and surrounding media in cylindrical coordinates
- Specifies the regions for dose to be scored
- Specifies the form of the output data, allowing data to be printed in tables or data files for plotting
- Specifies the type of radiation, electrons or photons, and the energies of these particles, monoenergetic or spectrum. Spectral data is obtained from spectrum files, containing energy bins and relative probabilities
- Specifies the source distribution, including source geometry and location
- Defines the limits restricting the number of histories to be scored, including history limit, time limit and minimum statistical error
- Selects the transport controls to be applied, including minimum energy cut offs and range rejection parameters [15]
The following example estimates the dose in water around a monoenergetic photon source distributed throughout the volume of a titanium ring. The photon energy is 27 keV. The titanium ring has an outer radius of 0.3 cm, an inner radius of 0.1 cm, a height of 0.2 cm and is placed at the centre of a cylinder of water whose height is 10 cm and radius is 5 cm. The cylinder of water is surrounded by air.

For the purpose of scoring the dose throughout the water, the geometry of the system was divided into many regions. There are 102 vertical (Z) slabs and 51 cylinders (R). The first and last slabs were 10 cm thick. The rest of the slabs were set to be 0.1 cm thick. The rings were each set to be 1 cm thick, with the exception of the last ring which was of

*Figure 2.7. Cross-sectional view of example geometry.*
thickness 5cm. The geometry was designed to have 10cm thick slabs at the top and bottom, as well as a 5cm thick outer ring. This was to contain the surrounding air. The geometry was filled with the desired materials, air, water and titanium by first filling the entire geometry with air, covering $Z = 1$ to 102 and $R = 1$ to 51. Next, water was added to the geometry, covering $Z = 2$ to 101 and $R = 1$ to 50. Finally, titanium was added to the geometry, covering $Z = 51$ to 52 and $R = 2$ to 2. The monoenergetic source of 27 KeV photons was added to the geometry as a volume distribution through the titanium. 10 million photons were simulated and the dose throughout the water was scored. The plotting control was set to plot the dose vs. distance along both the $Z$ axis and the $R$ axis.

The following input file was used with Dosrznrc to simulate the above example.

```plaintext
TITLE= Example input file, dosrznrc, 6711 seed in water

# The following sets the limits for the geometry
DOSE ZBOUND MIN= 1
DOSE ZBOUND MAX= 91
DOSE RBOUND MIN= 0
DOSE RBOUND MAX= 90

IWATCH= off

STORE INITIAL RANDOM NUMBERS= no
IRESTART= first
OUTPUT OPTIONS= material summary
STORE DATA ARRAYS= yes
```

25
#restarts

ELECTRON TRANSPORT= normal #normal, no interactions;
#Sets electron transport on/off

:stop I/O control:

:restart Monte Carlo inputs:

NUMBER OF HISTORIES= 10000000 #Sets the number of cascades

INITIAL RANDOM NO. SEEDS= 2, 3 #luxury level, seed
#Sets the luxury level and initial
#seed for Ranlux, the random number
generator subroutine

MAX CPU HOURS ALLOWED= 90 #Sets a time limit on the simulation

IFULL= dose and stoppers #dose and stoppers, entrance regions,
#pulse height distribution, scatter
#fraction;
#determines what doses are output

STATISTICAL ACCURACY SOUGHT= 0.0000 #Sets a limit on the accuracy

SCORE KERMA= no #no, yes;
#yes: score kerma wherever dose scored and estimate
#ratio of dose/kerma

:stop Monte Carlo inputs:

:restart geometrical inputs:

METHOD OF INPUT= groups #groups, individual:
#group: input groups of slabs of equal
#thickness
#individual: input Z of bottom of every
#slab

Z OF FRONT FACE= 0 #Z coordinate of first slab

NSLAB= 1, 100, 1 #Number of slabs
SLAB THICKNESS= 10, 0.1, 10 #Thickness of slabs (cm)
Corresponding to number of slabs
above

RADII= 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3,
1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7,
# Material Input

**MEDIA=** AIR, H2O, TI  
# the media in the example

**DESCRIPTION BY=** planes  
# planes, regions;  
# Sets whether the media are associated  
# with regions by specifying r and z  
# numbers or region numbers

**MEDNUM=** 1, 2, 3  
# Specifies the medium number

**START ZSLAB=** 1, 2, 51  
# Starting slab containing this medium

**STOP ZSLAB=** 102, 101, 52  
# Final slab containing this medium

**START RING=** 1, 1, 2  
# Starting ring containing this medium

**STOP RING=** 51, 50, 2  
# Final ring containing this medium

:stop geometrical inputs:

### Source Inputs:

**INCIDENT PARTICLE=** photon  
# electron, photon, positron, all, charged;  
# Type of particle

**SOURCE NUMBER=** 3  
# 0, 1, 2, 3, 4, 10, 11, 12, 13, 14, 20, 21  
# Number representing the source  
# distribution  
# number 3 is a solid ring

**SOURCE OPTIONS=** 0.1, 0.2, 14.9, 15.1  
# Inner radius, outer radius  
# minimum z, maximum z

**INCIDENT ENERGY=** monoenergetic  
# monoenergetic, spectrum;

**INCIDENT KINETIC ENERGY (MEV)=** 0.027  
# Energy of photons from source

:stop source inputs:

### MC Transport Parameter:

**Global ECUT=** 0.531  
# Electron cutoff for transport  
# in MeV (20 keV kinetic energy)

**Global PCUT=** 0.02  
# Photon cutoff for transport in  
# MeV (20 keV)

**Global SMAX=** 1e10  
# Maximum step size in cm (not  
# needed unless old PRESTA  
# algorithm is used)

**ESTEPE=** 0.25  
# Max fractional continuous  
# energy loss
# per step

XIMAX = 0.5 # Max first elastic scattering
# moment per step

Boundary crossing algorithm = exact # exact, PRESTA-I;
# exact: cross boundaries in single
# scattering mode (distance at
# which to go into single
# scattering mode determined by
# "Skin depth for BCA"
# PRESTA-I: cross boundaries with
# lateral correlations off and
# force multiple scattering mode

Skin depth for BCA = 3 # Distance from a boundary (in elastic MFP)
# at which the algorithm will go into single
# scattering mode

Electron-step algorithm = PRESTA-II # PRESTA-II, PRESTA-I;
# Determines the algorithm used to
# take into account lateral and
# longitudinal correlations in a
# condensed history step

Spin effects = On # Off (default), On;
# Turns off/on spin effects for electron
# elastic scattering

Brems angular sampling = KM # Simple, KM (default);
# Simple: leading term of Koch-Motz dist'n
# used to determine angle of Bremsstrahlung
# photons
# KM: Koch-Motz distribution used to
# determine angle

Brems cross-sections = BH # BH (default), NIST;
# BH: Bethe-Heitler cross-sections used
# NIST: NIST cross-sections used

Bound Compton scattering = On # Off (default), On;
# Off: Klein-Nishina used for Compton
# scattering
# On: Impuls approximation used for
# scattering

Pair angular sampling = Simple # Off, Simple (default), KM;
# Simple: use leading term of K-M
# KM: use complete Koch and Motz dist'n

Photoelectron angular sampling = On # Off (default), On;
# Off: Photoelectrons get direction
# of photon that creates them
# On: Sauter's formula is used

Rayleigh scattering = On # Off (default), On;
#Off: no coherent scattering
#On: simulates coherent scattering

Atomic relaxations= On #Off (default), On;
#On: emission of fluorescent x-rays

:Stop MC Transport Parameter:

:Start Variance Reduction:

BREM SPLITTING= Off #Off, On; #Bremsstrahlung Splitting

NUMBER OF BREMS PER EVENT= 1 # Only used if BREM SPLITTING= On

CHARGED PARTICLE RUSSIAN ROULETTE= Off #Off, On;
#On: use Russian Roulette to
#eliminate secondary charged
#particles with probability of
#survival=1/nbr_split

ELECTRON RANGE REJECTION= off #Off, On;
#On: if charged particle energy is
#below ESAVEIN and it cannot get out of
#current region with energy > ECUT, the
#particle is terminated

ESAVEIN= 0.0 #Energy below which range rejection is
#considered. This is a total energy.

RUSSIAN ROULETTE DEPTH= 0.0000 #play Russian Roulette with photons
#once they cross this Z plane

RUSSIAN ROULETTE FRACTION= 0.0000 #probability of photon survival--if
#this and RUSSIAN ROULETTE DEPTH
#are both 0, then no photon
#Russian Roulette is played

EXPONENTIAL TRANSFORM C= 0.0000 #Exponential path length biasing
#>0 stretched, <0 shortened

PHOTON FORCING= On #Off (default), On;
#On: force photons to interact in geometry

START FORCING= 1 #Start forcing at this interaction number

STOP FORCING AFTER= 1 #Number of photon interactions after which
#to stop forcing photon interactions
#Cross-sections will be scaled to force
#interactions

CS ENHANCEMENT FACTOR= 1.0, 10. #Photon cross-section scaling factors
CS ENHANCEMENT START REGION= 1, 1 #Regions in which to start applying
#above enhancement factors

CS ENHANCEMENT STOP REGION= 1, 1 #Regions in which to stop applying
#above enhancement factors
#region 1 is outside the geometry

:Stop Variance Reduction:

#############################
:start plot control:

PLOTTING= on #Off,On;
#On: create plots

LINE PRINTER OUTPUT= Off #Off,On;
#On: plot in .egslst file

EXTERNAL PLOTTER OUTPUT= On #Off,On;
#On: create .plotdat file

EXTERNAL PLOT TYPE= Point #Point,Histogram,Both;
#Point: output point plots in .plotdat file
#Histogram: output histogram plots in
#.plotdat

PLOT RADIAL REGION IX= 1 #Indices of cylinders for which to plot
#depth-dose data

PLOT PLANAR REGION IZ= 51 #Indices of slabs for which to plot dose
#vs. radius data

:stop plot control:

The following plots of dose vs. position along the Z and R axis were obtained from the
example output plot data file (.plotdat). Both plots show a decrease in dose with an
increase in distance from the source centre. The statistical error for each plot was less
than 1%.
Figure 2.8. Dose vs. Z position, source centre is at Z=15cm, R=0cm

Figure 2.9. Dose vs. r position, Z = 15cm
2.2.4 Flurznrc

Flurznrc is a similar code to Dosrznrc in that it simulates particles in RZ geometry. Like Dosrznrc, Flurznrc scores the dose deposited in desired regions around a source, but it has some extra features. As well as the dose deposited in a region, Flurznrc calculates the energy fluence in that region. The fluence of particles is useful in that by plotting fluence vs. energy for a certain region, the energy spectrum in that region is obtained. To obtain spectral data from Flurznrc, the user defines a list of energy bins for the fluence data to be scored. Flurznrc scores the total fluence in each energy bin for a variety of particles including electron primaries, photon primaries, electron secondaries, total primaries and total particles [15].

Flurznrc is similar to Dosrznrc in that the Main program initialises user variables obtained from an input file. The structure of the input file for Flurznrc is the same as that for Dosrznrc, with the addition of extra controls. Input/Output controls are added to pass on to Main the type of particles to be scored, the regions for spectra to be scored, the fluence spectra print options and the energy bin settings. Plotting controls are added to pass on to “Main” which particle spectra are to be plotted and the regions for spectra to be plotted [15].
The following additions are made to the user input file for use with Flurznrc.

: start I/O control:

PRINT FLUENCE SPECTRA= specified
  # all, specified, none;
  # all: output fluence spectra for all
  # regions the .egslist file
  # specified: output fluence spectra
  # only for those regions specified by
  # LIST FLUENCE START REGION and
  # LIST FLUENCE STOP REGION below

LIST FLUENCE START REGION= 42, 100, 150  # Regions to score the spectra
LIST FLUENCE STOP REGION= 45, 100, 156

IPRIMARY= total fluence
  # total fluence, electron primaries, include
  # brems secondaries, photon primaries, electron
  # secondaries;
  # electron primaries: score total fluence +
  # electron primaries with Bremsstrahlung
  # generated photons included as
  # primaries
  # include brems secondaries: score total
  # fluence + electron primaries
  # photon primaries: score total fluence +
  # first generation photons including
  # Bremsstrahlung
  # electron secondaries: score total fluence +
  # electron secondaries

SLOTE= 0.0001
  # if > 0, width of energy bins (MeV)
  # if = 0, input energy bins individually (see below)
  # if < 0, set up -SLOTE equal log bins
  # if = -999, set up equal bins on a log scale with the
  # top 10% of the bins equal on a linear scale

: stop I/O control:

: start source inputs:

INCIDENT ENERGY= spectrum
  # monoenergetic, spectrum;

SPEC FILENAME= I125.spectrum
  # file containing spectrum data

: stop source inputs:

: start plot control:

DRAW FLUENCE PLOTS= total
  # none, all, primaries, total;
  # none: plot total fluence only
  # all: plot total fluence and either primaries
The spectrum file used in the above example was to simulate the photon emissions from an $^{125}$I source. $^{125}$I.spectrum has been reproduced below.

```
#I125 spectrum
9, 0.02715, 0
0.02725, 0.405
0.02742, 1.E-6
0.02752, 0.756
0.03093, 1.E-6
0.03103, 0.201
0.03183, 1.E-6
0.03193, 0.0438
0.03544, 1.E-6
0.03554, 0.0666
```

The first figure, 9, specifies the number of energy bins. The column on the left specifies bin boundaries. Each figure in the column on the right specifies the weighting of the energy bin bounded by the figure in the left column and the previous figure in the left
column. An example spectrum, calculated by simulating a point source of $^{125}$I in water, was obtained for a distance of 5cm from the source.

![Example Spectrum](image)

**Figure 2.10. Example Spectrum, $^{125}$I point source in water, 5cm from the source**

After traversing 5cm of water the peaks are well defined with little low energy tails indicating that there is minimal scattering.
Chapter 3

The Modelling Of Doses From An $^{125}\text{I}$ Source

3.1 Seed geometry

The dimensions used to represent the Amersham OncoSeed 6711 in the following simulations were taken from "Theoretical evaluation of dose distributions in water about models 6711 and 6702 $^{125}\text{I}$ seeds", Jeffrey F. Williamson, et al, Medical Physics, volume 15, No. 6, Nov/Dec 1988.

![Diagram of 6711 seed dimensions](image)

*Figure 3.1. 6711 seed dimensions, from Williamson, et al [16]*
This representation differs slightly to the representation obtained from the OncoSeed 6711 technical data sheet (figure 2.4).

The representation of the 6711 seed from Williamson differs from that obtained from the technical data sheet in that it contains a thin coating of AgH, of thickness 4 microns, on the surface of the silver rod. The thickness of the titanium walls is 0.06mm in the representation from Williamson, instead of 0.05mm from the technical data sheet. Some assumptions were used when in representing the 6711 seed in the following simulations. One assumption was that the end welds of the seed were of equal size, being 0.06cm thick. In the production of the seeds there is no guarantee that the end welds will be of equal size. Another assumption was that the air gap within the seed was of constant size around the silver rod. There is nothing physical within the seed that would hold the core in place such that the air gap was constant. The final assumption was that the $^{125}$I was in the centre of the AgH coating. The $^{125}$I was represented as a cylindrical surface, 2μm below the surface of the AgH.

To allow the Main programs for Dosrznrc and Flurznrc to initialise the source variables, a source spectrum file (Iodine125.spectrum) was created that could be called by Main during the source inputs. The following table summarises the energy spectrum information contained in the source spectrum file. Each energy bin has a width of 0.1 keV. The sum of the weighting factors is 1.4724, the average number of photons above 27 keV emitted per disintegration.
To initialise the medium information the Main programs need to call cross-sectional information from a material data file. To produce this data file, PEGS4 was run for each material used in the simulations, producing cross-sectional information for these materials in individual data files. These data files were concatenated into one file, 6711.pegs4dat, which was used as the material data file for the following simulations. 6711.pegs4dat contained cross-sectional information for silver (Ag), silver hydride (AgH), titanium (Ti), air and water (H2O). The cross-sectional information was produced for photon interactions with energies between 1 and 50 keV. The following parameters were used in the construction of the cross-sectional information for each material.

**Silver**

Element, density = 10.5 g/cm³

Ag : Z = 47, A (atomic mass) = 107.870

**Silver Hydride**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.2</td>
<td>0.405</td>
</tr>
<tr>
<td>27.47</td>
<td>0.756</td>
</tr>
<tr>
<td>30.98</td>
<td>0.201</td>
</tr>
<tr>
<td>31.88</td>
<td>0.0438</td>
</tr>
<tr>
<td>35.49</td>
<td>0.0666</td>
</tr>
</tbody>
</table>

Figure 3.2. ¹²⁵I source spectrum file summary

To initialise the medium information the Main programs need to call cross-sectional information from a material data file. To produce this data file, PEGS4 was run for each material used in the simulations, producing cross-sectional information for these materials in individual data files. These data files were concatenated into one file, 6711.pegs4dat, which was used as the material data file for the following simulations. 6711.pegs4dat contained cross-sectional information for silver (Ag), silver hydride (AgH), titanium (Ti), air and water (H2O). The cross-sectional information was produced for photon interactions with energies between 1 and 50 keV. The following parameters were used in the construction of the cross-sectional information for each material.

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</tr>
<tr>
<td>31.88</td>
<td>0.0438</td>
</tr>
<tr>
<td>35.49</td>
<td>0.0666</td>
</tr>
</tbody>
</table>
Compound, density = 6 g/cm³

Ag : Z = 47, A = 107.870, PZ (relative number of atoms in compound) = 0.991935

H : Z = 1, A = 1.008, H density = 1, PZ = 0.92093

Titanium

Element, density = 4.54 g/cm³

Ti : Z = 22, A = 47.900

Air

Mixture, density = 0.0012048 g/cm³

C : Z = 6, A = 12.011, PZ = 1.03237 x 10⁻⁵

N : Z = 7, A = 14.007, PZ = 5.3917 x 10⁻²

O : Z = 8, A = 15.999, PZ = 1.4488 x 10⁻²

Ar : Z = 18, A = 39.948, PZ = 3.21168 x 10⁻⁴

Water

Compound, density = 1 g/cm³

H : Z = 1, A = 1.008, PZ = 2

O : Z = 8, A = 15.999, PZ = 1

Material data obtained from NIST Element Data index [17] and PEGS4 example data files.
3.2 Dose distribution along the transverse axis

Dosrznrc is a code that allows the dose distribution around a source to be mapped in cylindrical coordinates. A Monte Carlo simulation of a 6711 seed in water was conducted. 100 million particles were simulated. The following radial dose distribution was obtained.

![Graph of dose distribution](image)

*Figure 3.3. Dose distribution of a 6711 seed in water, measured along the transverse axis*

To compare the doses for both low and high distances, this data was plotted on a logarithmic scale.
Figure 3.4. Dose distribution of a 671\textsubscript{I} seed in water, measured along the transverse axis, plotted on a logarithmic scale

From the data it can be seen that the dose declines exponentially with distance. Dosrz\textsubscript{N}rc is useful in determining the dose at different positions around a source, but it serves no other function. It may be difficult to use the data from dosrz\textsubscript{N}rc to devise a method of finding the position of a source within a medium using measurements from solid-state detectors.
3.3 Spectrum simulation

Flurznrc is a code that allows the scoring of various fluence statistics at multiple points around a source. Flurznrc scores the fluence of particles at different energies, giving the spectrum of the radiation at each desired point. A 6711 seed in water was simulated using Flurznrc. 1 billion particles were simulated. Electrons and photons below 20 KeV kinetic energy were ignored as their energies are not in the region of concern. The following graph represents the spectrum at a point 0.045 cm from the source centre, on the r axis.

![Figure 3.5. Spectrum of a 6711 seed, measured in water, 0.045cm from the source centre on the transverse axis.](image-url)
The point of measurement was 0.045 cm from the centre of the source, which is 0.005 cm from the surface of the seed. After passing through the titanium casing, the spectrum of the radiation is still very sharp. The five initial gamma peaks of 27.2 keV, 27.47 keV, 30.98 keV, 31.88 keV, and 35.49 keV are clearly visible, but extra peaks have appeared at 22 keV, 25 keV and 25.5 keV. These peaks are silver x-ray peaks from interactions between the higher energy gamma rays and the silver rod.

The following graph represents the spectrum at a point 5 cm from the centre of the source, on the r axis.

Figure 3.6. Spectrum of a 6711 seed, measured in water, 5 cm from the source centre on the transverse axis.
After traversing 5 cm of water, the spectrum still contains well-defined peaks. The low energy tails on the photon peaks are due to the effects of scattering within the water. The effects of scattering appear to be minimal, indicating that the level of energy loss due to incoherent scattering is small. The spectrum retains its structure at large distances from the source. This indicates that the technique of spectroscopy may be used in the location of 6711 sources during brachytherapy treatment. For this to be possible, a property of the spectrum, which varies with distance, needs to be found.
3.4 Determination of the attenuation coefficient using dosrznrc

It can be seen from the radial dose plots (figures 3.3 and 3.4) that the dose is decaying exponentially with distance. If this exponential decay, or attenuation, is assumed to be due to the absorption of the radiation through the medium, and the source is assumed to be a point source, then the following equation would hold true.

\[ D_r \cdot 2 = D_0 \cdot r_0 ^2 \cdot e ^ {- \mu ( r - r_0 )} \]

Where \( D_0 \) is the dose measured at a fixed point \( r_0 \), and \( \mu \) is the attenuation factor. If no attenuation was present then this would reduce to

\[ D_r ^2 = D_0 r_0 ^2 \]

To calculate \( \mu \), a rearrangement of equation 1 gives

\[ \mu = - \frac{1}{r - r_0} \ln \left( \frac{D_r ^2}{D_0 r_0 ^2} \right) \]

\[ \mu = - \text{gradient of } \ln \left( \frac{D_r ^2}{D_0 r_0 ^2} \right) \text{ vs. } (r - r_0) \]

Since the gradient is desired, the constants may be eliminated giving

\[ \mu = - \text{gradient of } \ln \left( D_r ^2 \right) \text{ vs. } r. \]
The log of the dose times the square of the distance vs. distance was plotted on the following graph.

![Graph showing log of dose times square of distance vs. distance.](image)

**Figure 3.7. Log of (Dose \times distance squared) vs. distance, 6711 seed in water.**

Beyond 1 cm there is an almost linear relationship between \( \ln(Dr^2) \) and \( r \). The gradient of this was calculated to be 0.275 cm\(^{-1}\) with an error of 2%. At close distances there is not a linear relationship between \( \ln(Dr^2) \) and \( r \). This is due to the source having a finite size. Close to the source, the dose does not vary as a function of \( r^{-2} \). At larger distances, the source acts as a point source. Although this relationship appears linear after 1 cm, the gradient is gradually decreasing, indicating that the attenuation coefficient \( (\mu) \) is gradually increasing. The source of radiation was \(^{125}\)I, which does not emit monoenergetic photons. \(^{125}\)I emits photons with a range of energies between 27 keV and 35
keV. μ is dependent on the interaction cross-section of the medium, which varies with energy. The photoelectric cross-section of water increases with a decrease in energy at these energies. If the measured μ is considered to be the average μ in the above data, then an increase in μ with distance indicates that the average energy of the radiation passing through the medium decreases with an increase in distance. Using the attenuation coefficient (μ) and the measured dose at a point to calculate the distance to the source will not be accurate with a varying attenuation factor. A new method must be considered.
3.5 Determining the attenuation coefficient using Flurznrc

Since the attenuation coefficient of photons in water differs with photon energy, it may be possible to determine the attenuation coefficient for specific energies using separate energy peaks in the spectrum of $^{125}$I through the flurznrc code. Flurznrc was run for a 6711 seed in water. 1 billion particles were simulated. Electrons and photons below 20 keV kinetic energy were ignored. The following graph represents the spectrum at a point 0.045 cm from the source centre, on the r axis.

![Graph showing spectrum of 6711 seed in water](image)

*Figure 3.8. Spectrum of the 6711 seed in water, calculated at 0.045 cm from the centre of the source, on the transverse axis*
Since the peaks in the previous spectrum only contain two points, any comparison of data using peak heights would be inaccurate. Using the area under each peak would be a more accurate measure. To ensure an accurate measurement of the area under each peak the number of points in the plot was increased such that each peak spanned at least ten points. With the $^{125}\text{I}$ peaks being so narrow, a large amount of computer time is needed to reveal the fine detail in the spectrum over a 20 keV range. To reduce this computer time, three input files were written for \texttt{flurznrc}. Each input file was written to cover a different energy range in the spectrum. The first covered a 1 keV range at 27 keV, the second covered a 1.5 keV range at 31 keV and the third covered a 1 keV range at 35 keV. The following plot represents the spectrum of $^{125}\text{I}$ in the range of the 27 keV peaks at a distance of 0.045 cm from the source centre.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{spectrum_plot.png}
\caption{Spectrum of the 6711 seed in water, calculated at 0.045cm from the centre of the source, on the transverse axis. 27 keV region}
\end{figure}

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From figure 3.9 it can be seen that the two peaks at 27 keV are resolvable and well defined. The square appearance of the peaks is due to the original peaks in the input spectrum file.

The following plot represents the same spectrum at a distance of 4.9 cm from the source centre, on the transverse axis.

![Graph of spectrum of the 6711 seed in water, calculated at 4.9 cm from the centre of the source, on the transverse axis. 27 keV region](image)

Figure 3.10. Spectrum of the 6711 seed in water, calculated at 4.9 cm from the centre of the source, on the transverse axis. 27 keV region

After traversing almost 5 cm of water, the two peaks in the 27 keV region are still well defined, and have not lost their square appearance. The area under the 27.2 keV peak at a distance of 0.045 cm was found to be 1.31 cm$^2$. The area under the same peak, measured at 4.9 cm from the source was found to be $5.62 \times 10^{-5}$ cm$^2$. As expected, the area under the 27.2 keV peak has decreased with distance. This is a result of the photons being attenuated. Using the area under the individual peaks, the attenuation coefficient for the individual energies may be calculated.
Assuming the photons are attenuated exponentially with distance, the attenuation coefficient may be found by plotting the log of (area * distance squared) vs. distance. This is similar to how the overall attenuation coefficient was found using dose plots.

The attenuation coefficient for 27.2 keV photons was found to be $0.352 \text{ cm}^{-1} \pm 3\%$.

The previous method of calculating the attenuation coefficient using the area under the peaks at various distances was repeated for the 27.5 keV, 30.9 keV, 31.8 keV and 35.5 keV photons.
keV peaks. The following plot of log(area*distance squared) vs. distance was obtained for the 27.47 keV peak.

Figure 3.12. Log(area under 27.47 keV peak *distance squared) vs. distance for various distances. The gradient of the linear part of the curve is $-0.365 \text{ cm}^{-1} \pm 3\%$.

The attenuation coefficient for 27.47 keV photons was found to be $0.365 \text{ cm}^{-1} \pm 3\%$. 
The following plot of log(area*distance squared) vs. distance was obtained for the 30.9 keV peak.

Figure 3.13. Log(area under 30.9 keV peak *distance squared) vs. distance for various distances. The gradient of the linear part of the curve is $-0.305 \text{ cm}^{-1} \pm 2\%$

The attenuation coefficient for 30.9 keV photons was found to be $0.305 \text{ cm}^{-1} \pm 2\%$. 

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The following plot of log(area*distance squared) vs. distance was obtained for the 31.8 keV peak.

Figure 3.14. Log(area under 31.8 keV peak * distance squared) vs. distance for various distances. The gradient of the linear part of the curve is $-0.289 \text{ cm}^{-1} \pm 2\%$.

The attenuation coefficient for 31.8 keV photons was found to be $0.289 \text{ cm}^{-1} \pm 2\%$. 
The following plot of $\ln(\text{area} \times \text{distance squared})$ vs. distance was obtained for the 35.5 keV peak.

![Graph](image)

Figure 3.15. $\ln(\text{area under 35.5 keV peak} \times \text{distance squared})$ vs. distance for various distances. The gradient of the linear part of the curve is $-0.257 \, \text{cm}^{-1} \pm 1\%$

The attenuation coefficient for 35.5 keV photons was found to be $0.257 \, \text{cm}^{-1} \pm 1\%$
The attenuation coefficient for individual photon energies was found to decrease with an increase in energy, between the energies of 27.2 keV and 35.5 keV. One exception was the attenuation coefficient for 27.2 keV photons was slightly less than that for 27.47 keV photons, although both values overlap each other when errors are taken into consideration. The decrease in value for the attenuation coefficient with an increase in energy is attributed to the interaction cross-section of the photoelectric effect changing with energy. The following plot shows how the interaction cross-section varies with energy for the three forms of interaction between photons and water at low energies.

![Interaction Cross-sections for photons in water](http://www.nist.gov/M.J. Berger and J.H. Hubbell)

Figure 3.16. Interaction cross-sections for photons in water, from calculations using XCOM3, obtained from the National Institute of Standards and Technology (NIST).
From the interaction cross-section plot it can be seen that for energies below 27 keV the photoelectric effect dominates Compton scattering and Rayleigh scattering. The photoelectric effect interaction cross-section decreases exponentially with energy, accounting for the attenuation coefficient decreasing with energy. At 28 keV, however, the interaction cross-section for Compton scattering exceeds that for the photoelectric effect. The interaction cross-section for Compton scattering increases with energy for the low energy photon range that is considered. Photons that lose energy through the photoelectric effect lose all of their energy to the surrounding medium. Photons that lose energy through Compton scattering lose only a fraction of their energy. The energy lost by a photon through Compton scattering is dependant on the initial energy of the photon and the angle of scattering.

\[ h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 - \cos \theta)} \]  \[ \text{[18]} \]

Where \( h\nu' \) is the final photon energy after scattering, \( h\nu \) is the initial photon energy, \( m_0c^2 \) is the rest mass of an electron (0.511 MeV) and \( \theta \) is the angle the photon has been scattered through. The maximum energy loss incurred by a photon that has been Compton scattered would occur when the photon has been scattered in the reverse direction, when \( \theta = \pi \). The minimum final energy for a Compton scattered photon then becomes

\[ h\nu' = \frac{0.511 \times h\nu}{0.511 + 2h\nu} \]

The minimum energy for a 35.5 keV photon that has been Compton scattered is 31 keV. For photons scattered through small angles, the energy loss is minimal. Although the
interaction cross-section for Compton scattering is larger than that of the photoelectric effect for photon energies above 28 keV, the contribution of the Compton effect to the attenuation coefficient is minimal due to the small energy losses through Compton scattering at low energies. Hence the decrease in the value of the attenuation coefficient with an increase in energy is due to the photoelectric effect interaction cross-section decreasing.

Total attenuation cross-sectional data for photons in water was obtained from the National Institute of Standards and Technology (NIST), http://www.nist.gov. This data was converted to an attenuation coefficient for energies representing the photon emission energies from an $^{125}$I source. This data was placed in the table below for comparison with experimental measurements.

<table>
<thead>
<tr>
<th>Photon Energy (keV)</th>
<th>Attenuation Coefficient from NIST (cm$^{-1}$)</th>
<th>Measured Attenuation Coefficient (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.2</td>
<td>0.438 ±2%</td>
<td>0.352 ±3%</td>
</tr>
<tr>
<td>27.47</td>
<td>0.431 ±2%</td>
<td>0.365 ±3%</td>
</tr>
<tr>
<td>30.98</td>
<td>0.359 ±2%</td>
<td>0.305 ±2%</td>
</tr>
<tr>
<td>31.88</td>
<td>0.345 ±2%</td>
<td>0.289 ±2%</td>
</tr>
<tr>
<td>35.49</td>
<td>0.303 ±2%</td>
<td>0.257 ±1%</td>
</tr>
</tbody>
</table>

The measured attenuation coefficients were considerably lower than the standard attenuation coefficients from NIST. The standard coefficients include Compton and Rayleigh scattering cross-sections. Once a photon is scattered by one of these processes it
is disregarded. The measured coefficients were calculated from Monte Carlo simulations. These simulations obtained counts of photons at a point that included un-scattered photons and photons that had previously been scattered at a different point in the geometry. Hence the measured attenuation coefficients were lower than expected.

Since the attenuation coefficient varies with photon energy, the separate peaks in the spectrum of the 6711 seed will be attenuated by different amounts when measured at different distances from the source. The 27.2 keV peak will be attenuated the most, the 35.5 keV peak the least. By comparing the peak heights or the area under each peak, a system of determining the distance to the source by measuring the peak ratios may be constructed.
Chapter 4

Distance Measurements Using Spectroscopy Mode

4.1 Simulation of peak ratios

A 6711 seed in water was simulated using Flurznrc. 1 billion particles were simulated. Several spectra were obtained at points between 1 cm and 5 cm from the source, along the transverse axis. Two of these spectra are shown below.

Figure 4.1. Spectrum of the 6711 seed in water, 1 cm from the centre of the source, transverse axis
Figure 4.2. Spectrum of the 6711 seed in water, 5cm from the centre of the source, transverse axis.

The area under the combined 27.2 keV and 27.4 keV peaks for the spectrum at 1 cm from the source was 156.9 MeV$^{-1}$. The area under the combined 30.9 keV and 31.8 keV peaks for the spectrum at 1 cm from the source was 39.01 MeV$^{-1}$. The ratio of the combined 27 keV peaks to the combined 31 keV peaks at 1 cm was 4.022. For the spectrum at 5 cm from the source, this ratio was found to be 3.211. The ratio of the area under the 27 keV peaks to the area under the 31 keV peaks was found to decrease with distance from the source. This indicates that the 27 keV photons are being attenuated at a greater rate than the 31 keV photons. This is consistent with the attenuation coefficient calculations. The 27 keV photons have a higher attenuation coefficient than the 31 keV photons, resulting in the ratio of the area under the 27 keV peaks to the area under the 31 keV peaks decreasing with distance. A plot of peak ratio vs. distance up to 5 cm from the source was obtained from the data.
Assuming the area under the peaks in the spectrum are attenuated exponentially then

\[ A = A_0 e^{-\mu(r-r_0)} \]

for each peak where \( A_0 \) is the area under the peak at the distance \( r_0 \).

The ratio of the area under the 27 keV peaks to the 31 keV peaks, \( R \), is \( A^{27}/A^{31} \).

\[ \frac{A^{27}}{A^{31}} = \frac{A_0^{27} e^{-\mu^{27}(r-r_0)}}{A_0^{31} e^{-\mu^{31}(r-r_0)}} \]

\[ R^{27/31} = R_0 e^{-(\mu^{27} - \mu^{31})(r-r_0)} \]

Setting \( r_0 \) to be at the origin, \( r_0 = 0 \), gives.
Fitting an exponential decay to the above plot gives $R_0 = 4.25 \pm 0.3\%$, and

$(\mu^{27} - \mu^{31}) = 0.057\text{cm}^{-1} \pm 0.8\%$. This is consistent with the attenuation coefficient values calculated previously. There is now a function relating the 27 keV and the 31 keV peak ratios to the distance from the source along the transverse axis.

\[ R^{27/31} = R_0 e^{-\left(\mu^{27} - \mu^{31}\right)r} \]

The area under the combined 27 keV peaks was compared to the area under the 35.5 keV peak for spectra calculated at different distances along the transverse axis. A plot of peak ratio vs. distance up to 5cm from the source was obtained from the data.

Figure 4.4. Ratio of the area under the 27 keV peaks to the area under the 35.5 keV peak vs. distance, transverse axis
By fitting an exponential decay to the data, \((\mu^{27} - \mu^{35})\) was found to be \(0.093\text{cm}^{-1} \pm 0.8\%\). 

\(R_0\) was found to be \(14.41 \pm 0.3\%\). The function relating the 27 keV and the 35.5 keV peak ratios to the distance from the source along the transverse axis is 

\[ R^{27/35} = 14.41 e^{-0.093r} \]

The area under the combined 31 keV peaks was compared to the area under the 35.5 keV peak for spectra calculated at different distances along the transverse axis. A plot of peak ratio vs. distance up to 5 cm from the source was obtained from the data.

![Figure 4.5. Ratio of the area under the 31 keV peaks to the area under the 35.5 keV peak vs. distance, transverse axis.](image)

By fitting an exponential to the data, \((\mu^{31} - \mu^{35})\) was found to be \(0.036\text{cm}^{-1} \pm 3\%\). This is consistent with the attenuation coefficients calculated previously. \(R_0\) was found to be
3.39±0.4%. The function relating the 31 keV and the 35.5 keV peak ratios to the distance from the source along the transverse axis is

\[
R^{31/35} = 3.39e^{-0.036r}
\]

The distance from the point of measurement to the source may be determined if the detector at the point of measurement is used in spectroscopy mode, and the ratio of the area under any two peaks is calculated. One assumption is that in measurement, the two peaks at 27.2 keV and 27.47 keV, and the two peaks at 30.9 keV and 31.8 keV will be unresolvable. Another assumption is that the point of measurement is on the transverse axis of the seed. All of the calculations so far have been at points lying on the transverse axis. In practice, the point of measurement will be at an unknown angle to the axis of the seed. The previous methods for calculating the distance to the source will only be accurate if the ratio of the area under the peaks remains constant with changes in angle.
4.2 Simulation of peak ratios at different angles

The previous simulations were repeated, with the points of measurement set to acquire the spectrum of the 6711 source at different angles to the seed. The following diagram illustrates the angular reference used in the following simulations.

![Angular reference diagram](image)

*Figure 4.6. Angular reference for calculations at different positions around the seed. Calculations along the transverse axis are at $\theta = 90^\circ$.*

Flurznrc was executed using a 6711 seed in water. 1 billion particles were simulated. Measurements of the spectrum were taken up to 5cm from the centre of the source. The angle to the source was $30^\circ$ for all spectra. The following plot represents the 6711 seed spectrum, 1cm from the centre of the source.
Figure 4.7. Spectrum of the 6711 seed in water, 1 cm from the centre of the source, 30° from the source axis
The following plot represents the 6711 seed spectrum, 5cm from the centre of the source.

Figure 4.8. Spectrum of the 6711 seed in water, 5cm from the centre of the source, 30° from the source axis.

When calculated at 30°, after 5cm, the spectrum of the 6711 seed is still well defined. The $^{125}$I lines are resolvable, making it possible to accurately measure the area under the peaks.
The area under the combined 27 keV peaks was compared to the area under the combined 31 keV peaks for spectra calculated at different distances, 30° from the source axis. A plot of peak ratio vs. distance up to 5cm from the source was obtained from the data.

Figure 4.9. Ratio of the area under the 27 keV peaks to the area under the 31 keV peaks vs. distance, 30° from source axis.

By fitting an exponential decay to the plot it was found that $R_0 = 3.93 \pm 0.4\%$ and $(\mu^{27}-\mu^{31}) = 0.061 \pm 2\%$. This gives

\[ R^{27/31}_{30} = 3.93e^{-0.061r} \]
The ratio of the area under the 27 keV peaks to the area under the 31 keV peaks has been shown to vary with changes in angle. This shows that the method of finding the distance to the source using the ratio of two peaks in the spectrum is only accurate when the angle of the point of measurement with respect to the source axis is known. The previous simulations were repeated for a 6711 seed in water. The spectrum was measured at various distances up to 5 cm from the source, for various angles. The following plots of ratio vs. distance were obtained, for different ratios and angles, using the 27 keV, 31 keV and 35.5 keV peaks.

Figure 4.10. Ratio of the area under the 27 keV peaks to the area under the 31 keV peaks vs. distance, various angles
Figure 4.11. Ratio of the area under the 27 keV peaks to the area under the 35.5 keV peak vs. distance, various angles.
Figure 4.12. Ratio of the area under the 31 keV peaks to the area under the 35.5 keV peak vs. distance, various angles.

It can be seen that all of the peak ratios vary with changes in source angle. Simply finding the ratio of any two peaks in a measured spectrum is not enough to determine the distance to the source. The peak ratios are a function of both distance and angle. Assuming the distance from the source is of the order of centimetres, such that the geometry factor is a function of distance only and the anisotropy factor is a function of angle only, the peak ratios may be represented by separable functions of distance and angle.
16 \[ R = R_0 f(r) g(\theta) \]

\( f(r) \) was found to be \( e^{-\Delta \mu r} \).

Therefore

17 \[ R^{27/35} = R_0^{27/35} f(r)^{27/35} g(\theta)^{27/35} \]

and

18 \[ R^{31/35} = R_0^{31/35} f(r)^{31/35} g(\theta)^{31/35} \]

By measuring two ratios of three peaks in the spectrum, and solving two simultaneous equations, both the distance to the source and the angle the source makes with the detector may be found. This requires a function of angle, \( g(\theta) \), to be constructed.
To find $g(\theta)^{27/35}$, the ratio of the 27 keV peaks to the 35.5 keV peak ($R^{27/35}$) vs. angle was plotted below, for a fixed distance of 1 cm. The ratios were normalised by dividing by $R^{27/35}$ at $90^\circ$.

Figure 4.13. Plot of $R^{27/35}$ vs. angle, $r=1\text{ cm}$
To find \( g(\theta)^{31/35} \), the ratio of the 31 keV peaks to the 35.5 keV peak (\( R^{31/35} \)) vs. angle was plotted below, for a fixed distance of 1 cm. The ratios were normalised by dividing by \( R^{31/35} \) at 90°.

![Graph showing the ratio of 31/35 keV peaks vs. angle for a fixed distance of 1 cm.](image)

**Figure 4.14. Plot of \( R^{31/35} \) vs. angle, \( r=1cm \).**

To ensure the functions of angle and distance are independent, the normalised plot of the ratio of the area under the 27 keV peaks to the area under the 35 keV peak was repeated for distances between 1 and 5 cm from the source.
For different distances from the source, there is no apparent change in $g(\theta)$, except at low angles where a high level of attenuation and scattering through the thick titanium end welds has resulted in a low number of particles, and subsequently a high error. Hence, the functions of distance and angle are independent and separable at distances above 1 cm from the source. To construct a function to represent $g(\theta)$, more points are needed at various angles. Six points were not enough to accurately define a function representing $g(\theta)$.
Chapter 5

Comparison with experimental results

5.1 Experimental setup

Experimental measurements were conducted by Heidi Nettelbeck, fourth year Medical Radiation Physics student, University of Wollongong, 2002. These measurements involved placing an Amersham 6711 seed in a Perspex phantom and measuring the resulting spectrum at different depths within the phantom using a Cadmium Zinc Telluride detector.

Figure 5.1. Detector and phantom set up.
The detector used was an XR-100T-CZT Cadmium Zinc Telluride (Cd$_{0.9}$Zn$_{0.1}$Te) [19] detector, manufactured by Amptek, Massachusetts USA. The detector dimensions were 3mm x 3mm x 2mm [19]. The XR-100T-CZT has a top efficiency for photons in the range between 10 keV and 70 keV [14]. The typical energy resolution, measured using 122 keV photons from a $^{57}$Co source is 1.5 keV FWHM [19]. The detector was concealed behind a 0.3 mm stainless steel cover. The phantom was a Perspex block, 6cm x 6cm in cross-section, with holes placed 1cm apart to allow sources to be placed at different depths inside. All measurements of seeds placed inside the phantom are made along the transverse axis of the seed.
5.2 Experimental results

A 6711 seed was placed in position row 3 column 1 (3,1). The seed was approximately 1 cm from the detector. The following spectrum of the 6711 seed in this position were obtained.

![Spectrum of 6711 seed, position (3,1), 1cm from detector.](image)

From the previous spectrum it can be seen that the two photon peaks at 27.2 keV and 27.4 keV, as well as the two photon peaks at 30.9 keV and 31.8 keV are unresolvable, resulting in five visible peaks above 20 keV. The two peaks at 22.1 keV and 25.2 keV are x-ray peaks from the silver rod within the seed. The three peaks at 27.4 keV, 31.4 keV and 35.5 keV are from the iodine source within the seed. The previous plot was repeated for spectra of a 6711 seed, placed in positions (3,2), (3,4), and (3,5).
Figure 5.3. Spectrum of 6711 seed, position (3,2), 2cm from detector.
Figure 5.4. Spectrum of 6711 seed, position (3, 4). 4cm from detector.

Figure 5.5. Spectrum of 6711 seed, position (3, 5). 5cm from detector.
The heights of the three $^{125}$I peaks were measured for each position, and peak ratio plots were produced.

![Figure 5.6. Ratio of the height of the 27 keV peak to the height of the 31.4 keV peak.](image)

![Figure 5.7. Ratio of the height of the 27 keV peak to the height of the 35.5 keV peak](image)
Figure 5.8. Ratio of the height of the 31 keV peak to the height of the 35.5 keV peak

Assuming the peak ratios are a function of distance such that

\[ R^{a/b} = R_0 e^{-(\mu^a - \mu^b)r} \]

for peaks a and b.

For the ratio of the height of the 27 keV peak to the height of the 31.4 keV peak,

\[ R^{27/31} = R_0 e^{-(\mu^{27} - \mu^{31})r} \]

By fitting an exponential function to the plot, \( R_0 \) was found to be 4.20 ± 1.6% and 
(\( \mu^{27} - \mu^{31} \)) was found to be 0.039 cm\(^{-1} \) ± 13%. Previously, using Monte Carlo calculations, 
\( R_0 \) was found to be 4.25 ± 0.3% and (\( \mu^{27} - \mu^{31} \)) was found to be 0.057 cm\(^{-1} \) ± 0.8%.

For the ratio of the height of the 27 keV peak to the height of the 35.5 keV peak,
By fitting an exponential function to the plot, $R_0$ was found to be $14.2 \pm 1.7\%$ and $(\mu^{27} - \mu^{35})$ was found to be $0.048\text{cm}^{-1} \pm 11\%$. Previously, using Monte Carlo calculations, $R_0$ was found to be $14.41 \pm 0.3\%$ and $(\mu^{27} - \mu^{35})$ was found to be $0.093\text{cm}^{-1} \pm 0.8\%$.

For the ratio of the height of the 31 keV peak to the height of the 35.5 keV peak,

$$R_{27/35} = R_0 e^{-(\mu^{27} - \mu^{35})r}$$

By fitting an exponential function to the plot, $R_0$ was found to be $3.37 \pm 0.2\%$ and $(\mu^{31} - \mu^{35})$ was found to be $0.009\text{cm}^{-1} \pm 6\%$. Previously, using Monte Carlo calculations, $R_0$ was found to be $3.39 \pm 0.4\%$ and $(\mu^{27} - \mu^{31})$ was found to be $0.036\text{cm}^{-1} \pm 3\%$. 

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6.1 Experimental discussion

The experimental results were not consistent with the theoretical results. The measured values for the constants in the functions relating the peak ratios to distance were different to the theoretically calculated values. This is due to the experimental measurements being performed in a Perspex phantom whereas the theoretical results represent measurements in a water phantom. Perspex is not equivalent to water as an attenuating medium at low photon energies. Despite this, the experimental results show a change in the peak ratios with distance, as expected. This shows that although the experimental results do not match the theoretical results the method is still valid. Experimental results are needed for seeds within a water phantom. Experimental measurements at various angles to the source are also needed.
6.2 Assumptions

The purpose of this project was not to perfect a system for finding the location of brachytherapy seeds within the body, but to devise a method of approach to producing such a system. The method devised relies on the effects of the geometry factor and anisotropy factor on the peak ratios being separable functions of distance and angle respectively ($f(r)$ and $g(\theta)$). This was shown to be true for distances above 1 cm from the source but is not expected to be true close to the source. The simulations need to be repeated to calculate spectra at close distances to the source in order to study the relationships between distance and angle at these distances. When attempting to find functions representing $g(\theta)$, it was found that there were too few points in the plots to accurately fit appropriate functions to the plots. The simulations need to be repeated to measure spectra at a larger number of angles from the source.

An attempt was made to construct a system to locate brachytherapy seeds within the body using the radial dose function from the TG43 protocol. The approximation of $g(r) \propto e^{-\mu r}$ was found to be inaccurate as $\mu$ was found to be a function of energy. Since the photon spectra from brachytherapy seeds consist of peaks of various energies which are attenuated at different rates, $\mu$ is not constant with respect to $r$. 


6.3 Conclusion

A method of locating brachytherapy seeds within the body using real time measurements from semiconductor detectors was sought. The seed investigated was the OncoSeed 6711 from Amersham Health. The 6711 seed consisted of a radioactive source, $^{125}\text{I}$, coated onto a silver rod, encased in a titanium shell. $^{125}\text{I}$ decays via electron capture, releasing various electrons and photons of energies up to 35.5 keV. Due to the source being encased in titanium, only photons escape the titanium shell. The silver rod fluoresces in the presence of the $^{125}\text{I}$ photons, giving off characteristic silver x-rays. The photons that escape the seed have energies of 22.1 keV, 25.2 keV, 27.2 keV, 27.4 keV, 30.9 keV, 31.8 keV and 35.5 keV.

Monte Carlo simulations were used to calculate the dosimetric effects of these seeds in water. The Monte Carlo code used was Egsnrc version 2, a version of electron gamma shower 4 (egs4), modified by the National Research Council of Canada (NRC) to improve accuracy at low photon energies. Dosrznrc and Flurznrc were the programs used with Egsnrc to calculate the dose distribution and particle fluence around the seed.

The TG 43 protocol was used to investigate possible approaches to the solution of this problem. Brachytherapy seeds that are cylindrical may be represented in two dimensions using cylindrical coordinates. In two dimensions the TG43 protocol is

$$D(r,\theta) = S_k \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta) \quad [9]$$

where $D(r,\theta)$ is the dose distribution around the source, $S_k$ is the air kerma strength of the source, $\Lambda$ is the dose rate constant, $G(r,\theta)$ is the geometry factor, $g(r)$ is the radial
dose function and $F(r,\theta)$ is the anisotropy function. $G(r_0,\theta_0)$ is the geometry factor at a fixed reference point $(r_0,\theta_0)$. The reference point is chosen to be 1 cm from the centre of the source, on the transverse bisector, such that $(r_0,\theta_0) = (1, \pi/2)$.

The radial dose function accounts for attenuation and scattering in the medium. A method of finding the distance to the source was proposed using the radial dose function. The formula $g(r) = e^{-\mu r}$ was used for the radial dose function, where $\mu$ is the attenuation coefficient for photons in the medium. The dose distribution of the 6711 seed in water was calculated using Dosrznrc. The above formula for the radial dose function was found to be incorrect as $\mu$ was found to vary with distance. The attenuation coefficient was found to be different for different photon energies. Since photons at different energies were being attenuated at different rates, the average energy and hence the average $\mu$ were found to vary with distance from the source. The radial dose function could not be used to calculate the distance to the source. No attempt was made to construct a distance formula using a variable attenuation coefficient. This was due to the titanium shell encapsulating the source being of varying thickness at different angles about the seed. Such a formula would only be valid at a constant angle about the seed.

Since the attenuation coefficient was found to vary with energy it was necessary to consider the energy spectrum of the radiation from the source. Several spectra were obtained at different distances from a 6711 seed in water using Flurznrc. Since the photoelectric effect was dominant and scattering was minimal in the interactions between the photons and water, the energy spectrum from the source was found to retain its shape.
up to 5 cm from the source. All photon peaks were visible at 5 cm from the source. This allowed spectroscopy to be used as a tool for determining the distance to the source.

Since the attenuation coefficient of photons in water was found to decrease with an increase in photon energy, for photons in the desired energy range, the level of attenuation for each peak in the 6711 spectrum was found to vary. The lower energy peaks were attenuated at greater levels than the higher energy peaks. As a result, the ratios of the area under various peaks were found to vary with distance from the source. The following formulae were constructed for the peak ratios along the transverse axis.

\[ R_{27/35} = 14.41 e^{-0.093r} \]

for the ratio of the area under the 27 keV peaks to the area under the 35 keV peak and

\[ R_{31/35} = 3.39 e^{-0.036r} \]

for the ratio of the area under the 31 keV peaks to the area under the 35 keV peak.

These ratios are in the form \( R = R_0 e^{-\Delta \mu r} \), where \( \Delta \mu \) is the difference in attenuation coefficients for photons belonging to the two peaks.

These ratios were found to vary with changes in angle of the source to the point of measurement. The variation in angle was found to be independent of the distance from the source for distances in the order of centimetres. It was found that the peak ratios could be represented by a function consisting of separable functions of distance and
angle, $R = R_0 \, f(r) \, g(\theta)$, Where $f(r)$ is a function of distance from the source and $g(\theta)$ is a function of angle of the source.

Therefore

$$R^{27/35} = R_0^{27/35} \, f(r)^{27/35} \, g(\theta)^{27/35}$$

and

$$R^{31/35} = R_0^{31/35} \, f(r)^{31/35} \, g(\theta)^{31/35}$$

$f(r)$ was found to be $e^{-\Delta \mu r}$.

Hence

A) $R^{27/35} = 14.41 \, e^{-0.093r} \, g(\theta)^{27/35}$

And

B) $R^{31/35} = 3.39 \, e^{-0.036r} \, g(\theta)^{31/35}$

By calculating the area under the 27 keV, 31 keV and 35 keV peaks, performing ratios of the obtained areas and solving equations A and B simultaneously, the distance to the source as well as the angle of the source to the point of measurement may be determined.

There were not enough angular measurements to define a function for $g(\theta)$.

The formulas derived using Monte Carlo simulations were not consistent with the experimental results. This is due to the experimental measurements being conducted in a Perspex phantom and not water, as used in the simulations. The experimental setup did
not have the sensitive volume of the detector on the edge of the Perspex. This could also have contributed to the discrepancies in the results. The experimental results do conclude, however, that the peak ratios are a function of distance from the source, as expected.

The proposed model for finding the location of brachytherapy seeds within the body is a generic solution in that it is not fixed to the treatment of cancer in a specific location, such as the prostate. The model does not restrict the type of detector used, nor the location of the detectors. The model may be adapted for external detectors or interstitial detectors. The next step is to do a larger number of simulations to achieve a more accurate model, and to adapt the model to a practical system.
Chapter 7

References


