Characterization of novel electronic brachytherapy system

by

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Abstract

The Axxent device developed by Xoft Inc. is a novel electronic brachytherapy system capable of generating x-rays up to 50 keV. The objective of this study is to characterize the x-ray beam and to model the x-ray tube using the Geant4 Monte Carlo code. Spectral measurements are done using an Amptek XR-100T CdTe spectrometer. Attenuation curves are measured using both a NE-2571 farmer chamber and a PTW-23342 parallel plate chamber. 2-D dose distributions are measured using EBT Gafchromic films. The Geant4 Monte Carlo code is bench-marked against BEAMnrc results. HVL values and effective energies are obtained from spectral measurements, attenuation curve measurements, and Geant4 simulations. The results mostly agree within one standard deviation. Measurements show that the HVL decreases with beam angle. However, this trend is not observed in Geant4 results. 2-D dose distributions are compared with Geant4 Monte Carlo results. The agreement is mostly within 10%. However, there are significant differences aft of the source.
Résumé

La sonde Axxent, conçue par Xoft inc., est un nouveau système de curiethérapie électronique qui peut générer des rayons X avec une énergie maximum de 50 keV. L’objectif de cette étude est de décrire le spectre de rayons X émis et de créer un modèle du tube à rayons X en utilisant le code de Monte Carlo Geant4. Les mesures de spectres ont été réalisées à l’aide d’un spectromètre CdTe XR-100T de marque Amptek. Les courbes d’atténuation ont été mesurées à l’aide de deux chambres d’ionisation: une chambre NE-2571 de type Farmer et une chambre PTW-23342 de type chambre plate. Des films Garchromiques EBT ont été utilisés pour la mesure de distributions de dose en 2 dimensions autour de la source. Les résultats obtenus avec le code Geant4 ont été comparés avec les résultats générés grâce à un code de Monte Carlo différent: BEAMnrc. Les épaisseurs de demi-atténuation et les énergies effectives ont été également déduites des mesures spectrales, des courbes d’atténuation et des simulations de Geant4. Les résultats s’accordent avec une différence de moins d’un écart-type dans la plupart des cas. Les mesures indiquent que les épaisseurs de demi-atténuation diminuent avec l’angle du rayon choisi pour la mesure. Par contre, cette tendance n’est pas observée dans les simulations Monte Carlo avec Geant4. La comparaison entre les mesures et les calculs de Geant4 des distributions de dose en deux dimensions montre un accord généralement meilleur que 10 %. Néanmoins, il y a des différences importantes en arrière de la source.
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Chapter 1

Introduction
1.1 Electronic Brachytherapy Systems

1.1.1 A brief history

Brachytherapy is a form of cancer treatment involving radiation emitted at close proximity to the tumour [1]. Conventional brachytherapy uses radioactive isotopes as the radiation source. Compared with external beam radiation therapy, brachytherapy minimizes patient dose to the rest of the body, although the treatment is more invasive.

Electronic brachytherapy is a relatively new form of brachytherapy [14]. Instead of using radioactive isotopes, a kilovoltage x-ray tube is used to generate the radiation. An electronic brachytherapy system (EBS) eliminates the need for radioactive isotopes, which is a constant safety and security concern. Another advantage of EBS is the ability to adjust the tube potential, thus changing the radiation quality to achieve better dose conformity. However, progress is being made to develop brachytherapy systems that use two or more isotopes with different energies to achieve similar results [10].

One of the first electronic brachytherapy systems was developed in 1996 by Photoelectron Corporation and is used for interstitial radiosurgery [8][13]. The 40 kVp device is in the shape of a needle. The cathode is outside the patient while the target anode is placed inside the tumour. Thus, electrons are accelerated at the cathode and directed into the tumour via the needle. The main problem with this form of EBS, where the electrons are accelerated into the target, is the radiation generated along the needle as the electrons collide with the needle wall [14]. This
leakage thus irradiates normal tissue outside the tumour. Another potential problem is the heating of the target, which can damage the system and unintentionally burn the surrounding tissue. A cooling system is a viable option. However, this results in a larger needle, making the treatment more intrusive.

A new system developed in 2004 by Advanced X-Ray Technology Inc. circumvents the problem by having the x-ray target outside the patient [14]. The x-rays produced are again directed along a needle via a collimator. At the end of the needle is a second target. Photons incident on the second target undergo photoelectric interactions, resulting in fluorescent characteristic x-rays.

1.1.2 The Xoft Axxent

Over the past few years, Xoft Inc. has developed a novel EBS. The Axxent miniature x-ray tube is only 1 mm in diameter and 1 cm in length. Thus, the x-ray tube is implanted directly into the tumour. The x-ray tube is placed in a 5 mm water cooling catheter, allowing for a maximum air kerma strength of 1400 Gy cm\(^{-2}\) h\(^{-1}\) at 50 kVp and 300 \(\mu\)A beam current [17]. The operational lifetime of each source is at least 2 hours, sufficient for the duration of a multi-fraction treatment. Currently, the Axxent has received FDA approval for partial breast irradiation following lumpectomy.
1.2 Description of thesis

1.2.1 Purpose and objective

This study is the beginning of a larger goal of developing a Monte Carlo based treatment planning system for the Xoft Axxent. The plan has three main objectives: 1) to determine the beam quality and dosimetric parameters of the novel radiation generating device, 2) to investigate the radiation quality effects of the low energy x-rays generated, and finally 3) to build a treatment planning system to be used in a clinical setting.

The main objective of this study is to characterize the radiation produced by the miniature x-ray tube and to model the tube using a Monte Carlo code. The characterization involves three types of measurements: a) x-ray spectra, b) half value layer (HVL), and c) dose distribution. The x-ray spectra are measured using a CdTe spectrometer. The HVLs can be obtained in two ways, from measurements of attenuation curves using an ionization chamber and from kerma calculations based on measured spectra. Dose distributions are measured using EBT Gafchromic films.

In addition to the three characterizations, additional properties of the x-ray tube have to be investigated. The miniature x-ray tube has an operational lifetime of two hours. It is therefore likely that patients undergoing multi-fraction treatment may be treated with several different sources over the course of the treatment. To account for changing output due to source aging or due to a new source, the current procedure is to calibrate the source in a well chamber, attached to the control console, at the beginning of each fraction. However, a simple measurement of source strength does
not account for possible changes in beam quality. Therefore, this study also seeks to determine the extent of source aging and source-to-source variations.

Spectral, HVL, and dose measurements are compared with Monte Carlo results using the Geant4 code. The EGSnrc/BEAMnrc Monte Carlo code is the code of choice for medical physics applications in terms of accuracy, speed, and user-friendliness. However, for this study, it does not have sufficient ability to model the complex geometries of the x-ray tube. To verify that the Geant4 simulation is properly implemented, it is necessary to compare Geant4 and EGSnrc/BEAMnrc results for simple geometries.

1.2.2 Thesis organization

The thesis has a total of 6 chapters and is separated into parts: experiments and Monte Carlo. This distinction can be seen either in a chapter or sections within a chapter. Chapter 2 is a brief overview of the physics background and theory relevant to the experimental part of the study. Chapter 3 discusses the experimental methods and procedures. Chapter 4 deals with the implementation of the Geant4 Monte Carlo code. Chapter 5 contains all the results and discussions on both experiments and simulations. Chapter 6 concludes and summarizes the thesis.
Chapter 2

Theory and Background
2.1 Kilovoltage x-ray production

2.1.1 Bremsstrahlung radiation

Kilovoltage electrons mostly undergo ionization collisions, colliding with orbital electrons and losing energy according to the collisional stopping power \( S_{\text{col}} \) [21]. The collisional stopping power, \( S_{\text{col}} \), for a free electron is given by the Moller cross section [27]:

\[
\frac{S_{\text{col}}}{\rho} = \frac{2\pi r_e^2 mc^2}{u} \frac{1}{\beta^2 A} \left[ \ln \left( \frac{T}{I} \right)^2 + \ln(1 + \frac{\tau}{2}) + F^{-}(\tau) - \delta \right]
\]

and,

\[
F^{-}(\tau) = (1 - \beta^2) \left[ 1 + \frac{\tau^2}{8} - (2\tau + 1)\ln 2 \right]
\]

where \( \rho \) is the medium density, \( r_e = 2.818 \text{ fm} \) is the classical electron radius, \( m \) is the mass of the electron, \( c \) is the velocity of light, \( u = 1.6605655 \times 10^{-24} \text{ g} \) is the atomic mass unit, \( \beta \) is the velocity of the incident electron divided by the velocity of light, \( Z \) is the atomic number, \( A \) is the atomic mass number, \( T \) is the kinetic energy of the electron, \( I \) is the mean excitation energy of the medium, \( \tau \) is the kinetic energy of the electron divided by its rest energy, and \( \delta \) is a density correction term. The important dependencies in the kilovoltage range are:

\[
S_{\text{col}} \propto \frac{1}{\beta^2 A} \ln(T)
\]

where \( \nu \) is the velocity of the electron. If the non-relativistic case is considered, when \( T \ll mc^2 \), the kinetic energy \( T \) is proportional to the square of the velocity. Taylor
expanding the \( \ln \) term gives the upper bound to equation 2.3:

\[
S_{\text{col}} \propto \frac{1}{v^2} \frac{Z}{A} \ln(v^2) \\
\approx \frac{1}{v^2} \frac{Z}{A} \left( v - \frac{v^2}{2} + \cdots \right) \\
< \frac{1}{v^2} \frac{Z}{v} = \frac{1}{\frac{v}{A}}.
\]

Therefore, at the lower energy limit, the collisional stopping power is inversely proportional to the electron velocity. Note that \( \frac{Z}{A} \) is approximately constant (0.4~0.5) over all elements except for hydrogen, where it is equal to unity.

Electrons can also interact with the nucleus and produce bremsstrahlung photons [21]. Bremsstrahlung production is governed by the radiative stopping power \( S_{\text{rad}} \) [4]:

\[
S_{\text{rad}} = \alpha r_e^2 Z^2 \frac{N_A}{A} B_{\text{rad}} E
\]

where \( \alpha \) is the fine structure constant, \( N_A \) is Avogadro’s number, \( B_{\text{rad}} \) is a complex function which is approximately constant for non-relativistic energies, and \( E \) is the total energy of the electron. Thus, the radiative stopping power increases with energy and with \( Z \).

Figure 2.1 [21] plots the energy dependence of the radiative stopping power \( S_{\text{rad}} \), collisional stopping power \( S_{\text{col}} \), and the total stopping power \( S_{\text{tot}} \) for two materials: carbon \( (Z = 6) \) and lead \( (Z = 82) \). As mentioned, the collisional stopping power is inversely proportional to the electron velocity at low energies. This is seen as a straight line with a negative slope in log-log scale. At kilovoltage energies, the radiative stopping power is small compared to the collisional stopping power. For
the energy range of interest (50 keV), the collisional stopping power dominates by two orders of magnitude. As a result, the amount of energy going into photon production is only a small fraction of the primary electron energy. Most is lost as heat from electron collisions.

2.1.2 Characteristic radiation

Characteristic photons are created from vacancies in electron orbits. For the energies of the miniature x-ray tube (up to 50 keV), there are only three physical processes capable of generating vacancies [4]: photoelectric effect, Compton scattering, and electron impact ionization (eii).
For the photoelectric effect, the incident photon is completely absorbed by the orbiting electron, which is ejected out of the atom. In Compton scattering, the incident photon scatters off an orbital electron. The electron gains sufficient energy to escape the atom, leaving behind a vacancy. Electron impact ionization occurs when an incident electron collides with an orbital electron, creating a vacancy.

With a transmission x-ray target, electron impact ionization mostly occurs near the surface of the target while photoelectric and Compton interactions occur deeper in the target [19]. Eii is directly produced by primary electrons while photons for photoelectric and Compton interactions have to be produced by bremsstrahlung from the primary electrons first. Bremsstrahlung photons are more penetrating than the primary electrons, resulting in photon interactions deeper in the target.

If the transmission target is thin, the bremsstrahlung photons mostly transmit through the target. As a result, the characteristic photons from a thin target are mostly from eii. On the other hand, thick targets attenuate the characteristic photons generated by eii on the surface. Only characteristic photons generated deeper in the target can transmit through. Therefore, characteristic photons from a thick target are generated by photon interactions rather than electron impact ionization.

2.2 Half value layer

The half value layer (HVL) is the most important beam specifier for kilovoltage x-rays [16]. For the energy range of concern, the HVL is often expressed in terms of mm aluminium. In literature, the HVL is the “thickness that attenuates the
beam [intensity] to 50 %” [21]. This definition describes the case for mono-energetic photons and the beam intensity refers to the number of photons incident normal to an area. For this study, a slightly different approach is taken to account for the fact that the x-ray spectrum comprises of a range of energies. The HVL here is defined as the thickness that attenuates the air kerma of a beam by 50 %.

The HVL measured from an attenuation curve can be compared with the HVL calculated from a spectral measurement. To calculate the spectral HVL, the thickness of aluminium that attenuates the open beam (unattenuated) air kerma by half is determined. To extract the HVL from an attenuation curve measurement, the thickness of aluminium that attenuates the ionization chamber signal by half is determined. It can be shown that the ionization chamber signal is proportional to the air kerma for kilovoltage x-rays. The chamber signal is proportional to the exposure as calculated from the calibration coefficient, $N_X$. The exposure, in turn, is proportional to the air kerma [3]:

$$K_{air} = X \left( \frac{W_{air}}{e} \right) \frac{1}{1-g} \approx X \left( \frac{W_{air}}{e} \right) = MN_X \left( \frac{W_{air}}{e} \right)$$

where $X$ is the exposure, $(W_{air}/e) = 33.97$ J/C is the energy required to create one coulomb of charge in air under normal temperature and pressure, $M$ is the measured signal, and $g$ is the radiative fraction which is approximately 0 for kilovoltage x-rays. Thus, the HVL is the thickness of aluminium that attenuates the open beam measured signal by half.
2.3 CdTe Spectrometry

2.3.1 Distortion effects

Figure 2.2: Detector efficiency for a 1 mm thick CdTe crystal with 1 mil (25 μm) and 10 mil (250 μm) beryllium window. The response of the detector is independent of the beryllium window thickness at energies above 10 keV but diverges at lower energies. Also, above 100 keV, Compton scattering becomes significant as the photoelectric effect no longer accounts for the total photon interaction in the crystal.

A perfect detector in x-ray spectrometry has the following three properties [28]: a) uniform energy response, b) complete energy deposition, and c) no carrier trapping. Failure to satisfy each of these criteria results in distortion effects.
Figure 2.3: The tailing phenomenon due to carrier trapping for CdTe and CdZnTe crystals [29].

Figure 2.2 shows the detection efficiency (probability of primary photon interaction) of a 1 mm thick CdTe crystal with a beryllium window. The decreased detection efficiency below 10 keV is due to attenuation by the window. The decreased efficiency above 50 keV is due to primary photon transmission through the thin CdTe crystal.

Note figure 2.2 alone does not represent the energy response of the detector. Incident photons interacting in the crystal do not necessarily deposit all their energy. If a photoelectric interaction occurs, it is possible for a characteristic photon to escape the crystal. If a Compton interaction occurs, the scattered photon can also escape the crystal. These effects result in partial energy deposition and the detector may register these photons at lower energies.

Photons deposit energy in the crystal by creating electron-hole pairs, with the number of pairs proportional to the energy deposited. An electric potential is set across the crystal to collect the charge carriers. However, these carriers can be
trapped due to drifting and imperfections of the crystal [28]. The photon is then registered at lower energies. The result is a phenomenon called *tailing* and is shown in figure 2.3. The incident 59.5 keV mono-energetic beam is measured as a 59.5 kVp spectrum with photons registered at lower energies. The amount of carrier trapping is determined by factors such as crystal composition, crystal impurities, crystal size, and electric field strength.

### 2.3.2 Calculating HVL from spectrum

Air kerma, which will be denoted simply as $K$, for a mono-energetic photon beam is related to the particle fluence $\Phi$ [21]:

$$ K = \Phi \left( \frac{\mu}{\rho} \right)_{\text{air}} \overline{E}_{tr} $$

where $\left( \frac{\mu}{\rho} \right)_{\text{air}}$ is the mass attenuation coefficient of air and $\overline{E}_{tr}$ is the average energy transferred. Equation 2.6 can be expanded using the definition of $\mu_{tr}$, where [3]:

$$ \mu_{tr} = \mu \frac{\overline{E}_{tr}}{E} $$

Therefore,

$$ K = E \Phi \left( \frac{\mu_{tr}}{\rho} \right)_{\text{air}} $$

where $E$ is the photon energy. The attenuation of a mono-energetic beam in terms of kerma is:

$$ K = E \Phi \left( \frac{\mu_{tr}}{\rho} \right)_{\text{air}} e^{-\mu x} $$

(2.7)
where $\mu$ is the attenuation coefficient of the attenuator material and $x$ is its thickness.

Finally, the kerma for a heterogeneous spectrum is the sum of mono-energetic kerma:

$$\frac{K_f}{K_i} = \frac{\sum_{E=0}^{E_0} E\Phi \left( \frac{\mu_{en}}{\rho} \right)_{air} e^{-\mu x}}{\sum_{E=0}^{E_0} E\Phi \left( \frac{\mu_{tr}}{\rho} \right)_{air}} = \frac{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{en}}{\rho} \right)_{air} e^{-\mu x}}{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{tr}}{\rho} \right)_{air}}$$

(2.8)

where $K_f$ is attenuated kerma, $K_i$ is the incident kerma, and $E_0$ is the maximum energy of the spectrum. The photon fluence $\Phi$ is measured by the detector count $N$ corrected for the detector efficiency, which for the energy range of concern (9~50 keV) the efficiency is 100% (see figure 2.2). Note that the summation is over the entire energy range and each term in the equation is dependent on the photon energy.

For the energy range of concern, the mass energy transfer coefficient can be approximated by the mass energy absorption coefficient:

$$\left( \frac{\mu_{en}}{\rho} \right) = (1 - g) \left( \frac{\mu_{tr}}{\rho} \right) \sim \left( \frac{\mu_{tr}}{\rho} \right)$$

(2.9)

where $g$ is the radiative fraction and approaches zero for kilovoltage energies. Thus, values for $\left( \frac{\mu_{en}}{\rho} \right)$, which can be found in the NIST database, can substitute for $\left( \frac{\mu_{tr}}{\rho} \right)$.

Equation 2.8 becomes:

$$\frac{K_f}{K_i} = \frac{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{en}}{\rho} \right)_{air} e^{-\mu x}}{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{en}}{\rho} \right)_{air}}.$$ 

(2.10)

The $1^{st}$ HVL is then the thickness of attenuator $x$ that reduces the kerma to 0.5 of
the initial kerma:

$$0.5 = \frac{K_f}{K_i} = \frac{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{en}}{\rho} \right)_{air} e^{-\mu(HVL)}}{\sum_{E=0}^{E_0} EN \left( \frac{\mu_{en}}{\rho} \right)_{air}}.$$  

### 2.3.3 Calculating error for HVL from spectrum

Equation 2.10 is a multi-variable equation with error contributions from the following quantities: the energy $E$, the photon count $N$, the attenuation coefficient $\mu$, and the mass energy absorption coefficient of air $\left( \frac{\mu_{en}}{\rho} \right)_{air}$, which for the remaining part of this section will be simplified to $\left( \frac{\mu_{en}}{\rho} \right)$. Each quantity has $n$ variables corresponding to the number of energy bins in the spectrum. For example, there are $n$ number of energy variables $E_1, E_2, \ldots, E_n$. Therefore, equation 2.10 is a function of $4n$ variables:

$$\frac{K_f}{K_i} = f \left( E_1, N_1, \mu_1, \left( \frac{\mu_{en}}{\rho} \right)_1, E_2, N_2, \mu_2, \left( \frac{\mu_{en}}{\rho} \right)_2, \ldots, E_n, N_n, \mu_n, \left( \frac{\mu_{en}}{\rho} \right)_n \right)$$

The absolute error for the ratio of final and initial kerma is given by the rules of error propagation for a multi-variable equation:

$$\Delta \left( \frac{K_f}{K_i} \right) = \sum_{1}^{n} \left| \frac{\partial f}{\partial E} \right| (\Delta E) + \sum_{1}^{n} \left| \frac{\partial f}{\partial N} \right| (\Delta N) + \sum_{1}^{n} \left| \frac{\partial f}{\partial \mu} \right| (\Delta \mu) + \sum_{1}^{n} \left| \frac{\partial f}{\partial \left( \frac{\mu_{en}}{\rho} \right)} \right| (\Delta \left( \frac{\mu_{en}}{\rho} \right)) \quad (2.11)$$
where the $\Delta$ symbol represents the error associated with the variable. The partial derivatives of each variable are:

\[
\frac{\partial f}{\partial E} = \frac{N \left( \frac{\mu_{en}}{\rho} \right) K_i}{K_i} \left( e^{-\mu x} - \frac{K_f}{K_i} \right)
\]
\[
\frac{\partial f}{\partial N} = \frac{E \left( \frac{\mu_{en}}{\rho} \right) K_i}{K_i} \left( e^{-\mu x} - \frac{K_f}{K_i} \right)
\]
\[
\frac{\partial f}{\partial \left( \frac{\mu_{en}}{\rho} \right)} = \frac{EN K_i}{K_i} \left( e^{-\mu x} - \frac{K_f}{K_i} \right)
\]
\[
\frac{\partial f}{\partial \mu} = -x EN \left( \frac{\mu_{en}}{\rho} \right) e^{-\mu x}.
\]

Finally, the error in HVL is related to the error in the ratio of kerma by the partial derivative with respect to the attenuator thickness:

\[
\Delta(HVL) = \Delta \left( \frac{K_f}{K_i} \right) \frac{1}{n} \sum_{1}^{n} \left| \frac{\partial f}{\partial x} \right|^{-1}.
\]

where

\[
\frac{\partial f}{\partial x} = -\mu EN \left( \frac{\mu_{en}}{\rho} \right) e^{-\mu x}.
\]

### 2.4 Recommended setup for measuring HVL using an ionization chamber

When measuring attenuation curves using ionization chambers, the primary confounder is scattered radiation from the attenuator and other surrounding structures
The general recommended setup is shown in figure 2.4, and is often referred to as ‘narrow beam geometry’. The beam should encompass the entire sensitive volume of the detector but be as narrow as possible to avoid scatter from the attenuator. To further reduce scatter radiation, the detector is placed far away from the source at the recommended source-detector distance of 100 cm.

Figure 2.4: Recommended HVL experimental setup as illustrated by Khan [20].

Additional recommendations for the measurement of HVL for kilovoltage x-ray beams are given in the AAPM TG-61 protocol [16]. Some of the recommendations state that:

- the detector should be relatively insensitive to changes in spectrum caused by hardening from additional attenuators,
- a monitor chamber should be used to correct for variations in the output rate,
- the monitor chamber should be placed between the source and collimator but in such a way that it does not perturb the primary beam going through the collimator, and,
- the purity of the attenuator material should be at least 99.9 %.
These recommendations ensure that the HVL beam quality is measured accurately and that it is not biased due to confounding effects.
Chapter 3

Materials and Methods
3.1 Spectral measurements

3.1.1 Materials and setup

The spectrometer used in this study is the Amptek XR-100T cadmium telluride spectrometer. The CdTe crystal size is $3 \times 3 \times 1 \text{ mm}^3$ and the beryllium window is 4 mil (0.1 mm) thick. The spectrometer is connected to an Amptek PX4 pulse processing system, which acts as a shaping amplifier, multichannel analyzer, and high voltage power supply. The PX4 processes the XR-100T signal digitally, eliminating the need for traditional analogue op-amp circuits. The PX4 is connected to, and controlled by, a Microsoft Windows based PC using the vendor supplied software.

The miniature x-ray tube emits radiation in all directions, though not isotropically. To minimize scatter from the table, the x-ray tube is suspended 20 cm in air by a custom made lucite apparatus shown in figure 3.1. The apparatus can rotate about a vertical axis passing through the tip of the source, allowing for measurements at angles up to $90^\circ$.

The spectrometer is placed either at 25 cm or 1.5 m from the source. The lead collimator shown in figure 3.1 is 2.5 cm away from the source, between the source and the detector. The collimator is $10 \times 10 \text{ cm}^2$ and is 2 mm thick with a circular aperture 0.5 cm in diameter.

The spectrometer itself has a set of variable tungsten collimators each 2 mm thick. For this study, a 2 mm diameter collimator is attached to the spectrometer. Because of the small collimator size, care must be taken to ensure that the spectrometer is aligned with the collimator and the source. A laser pointer is attached to the
Figure 3.1: The miniature x-ray tube suspended in air by the lucite apparatus. The lead collimator foil is also shown forward of the source.

The software settings for the spectrometer are as follows: 512 energy bins, 500 V operating voltage, and a total count of 500,000 per spectrum. The remaining settings are set to the default configuration for a XR-100T detector.

Shielding of the operator for radiation safety is essential with the Xoft Axxent. The x-ray tube does not extend more than one meter from the controller. Thus, the operator is in close proximity to the source. Furthermore, for spectral and ionization chamber measurements, the source is placed in air. To shield the operator, a box lined with 2 mm lead is used to partially enclose the experiment. In addition, a
commercial portable radiation shield, 0.5 m wide and 2 m high, further protects the operator.

3.1.2 Calibration

The PX4 analyzer measures a signal in mV. This signal is proportional to the photon energy but requires calibration to be converted to keV. According to the vendor, the equation relating the signal strength to the photon energy is modeled by a line equation:

\[ y = mx + b \]

where \( x \) is the bin number and \( y \) is the corresponding photon energy. \( m \) and \( b \) are unknowns to be determined from calibration.

As such, two reference points are used to solve for the two unknowns. The radioactive decay of Ba-133 has a peak at 31.0 keV. The second calibration point uses the yttrium K-\( \alpha \) characteristic of the x-ray tube spectrum at 14.9 keV. For this study, the gain is adjusted such that each bin is approximately 0.1 keV.

3.1.3 Correcting for spectrometer artifacts

The EGSnrc/DOSXYZnrc Monte Carlo code is used to determine the detector response. The script for running the code is written by M. Bazalova [25]. For each 0.1 keV energy bin, a simulation is done where monoenergetic photons of the corresponding energy are incident on the CdTe crystal. The distribution of energy deposition of the monoenergetic photons gives the response function of the detector.
This method does not account for the tailing effect due to carrier trapping mentioned in section 2.3.1. However, the tailing effect is not significant for the crystal size and operating voltage used in this study [29].

A Matlab routine supplied by Bazalova is used to apply the stripping method [28]. Taking a raw spectrum as input, the Matlab routine iteratively corrects each energy bin starting with the highest energy bin. Photons, which do not completely deposit all their energies and thus are detected as lower energy photons, are re-registered to higher energies according to the detector response function.

### 3.1.4 Correction for distances

HVLs calculated from measured spectra are compared with HVLs calculated from attenuation curve measurements. The ionization chamber is placed at a different distance from the source than the spectrometer. This is because the spectrometer requires a much lower count rate and is positioned further away from the source. Therefore, it is necessary to correct for air attenuation, which can significantly affect the lower energy portion of the spectrum.

Correction is done by multiplying the photon count in each energy bin by the attenuation factor $e^{\mu x}$, where $\mu$ is the attenuation coefficient of air as a function of energy and $x$ is the extra distance of air. 1 m of air attenuation can effect the HVL by 10 % for a 40 kVp beam in the forward direction.
3.1.5 Calculating HVL and effective energy

To calculate HVL from a spectrum, mass energy absorption coefficient of air \( \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{air}} \) and mass attenuation coefficient of aluminium \( \left( \frac{\mu}{\rho} \right)_{\text{Al}} \) data from 5 to 60 keV are taken from the NIST database [24]. A sixth order polynomial fit on a log-log scale is used to parameterize the variables.

Calculation of HVL, as describe by equation 2.10, is done using a Microsoft Excel spreadsheet written by Verhaegen. Initial and final kerma are calculated for photons in each energy bin. The Excel built-in solver is used to iteratively determine the thickness of Aluminium necessary to attenuate the air kerma by half to determine the 1\textsuperscript{st} HVL.

Given the 1\textsuperscript{st} HVL, the attenuation coefficient \( \mu \) can be determined:

\[
HVL = \frac{\ln(2)}{\mu}
\]

Using the same polynomial fit used to calculate HVL, the energy that corresponds to the value of the attenuation coefficient is the effective energy.
3.2 Attenuation curve measurements

3.2.1 Materials and setup

Two ionization chambers are considered for this study: the NE-2571 farmer and the PTW-23342 parallel plate chambers. There is debate over which chamber to use. The PTW-23342 has a very thin window and almost uniform low energy response (8~35 keV), in accordance to TG-61 recommendations [16]. However, the collecting volume is extremely small and the signal is very weak. Normally, low signals would not be a concern since one can set a longer collection time. However, the miniature x-ray tube has a short 2 hrs lifetime and the measurement must be done as fast as possible to minimize effects due to changing source output. The NE-2571 chamber has a much larger collecting volume. However, because of the 1.5 mm graphite wall, the energy response must be corrected for. As a compromise, experiments are done using both ionization chambers. A second farmer-type chamber, placed at 90° to the source-collimator-detector line, is used to monitor the beam output. For both primary and monitor chambers, the signals are collected using Keithley 6517A electrometers.

The source is held in air by the lucite apparatus as described in section 3.1.1. The 0.5 cm diameter lead collimator, also held in place by a groove in the apparatus, is 2.5 cm from the source. Aluminium foils of 99.9% purity are used as attenuators and placed 5 cm from the source. The foils are 10×10 cm² and are 0.1 to 1 mm thick. A micrometer is used to measure the thickness of the foils.

The recommended distance between the source and detector is one meter [16].
However, the miniature x-ray tube is a brachytherapy source that irradiates at close distances. To obtain an adequate signal (∼pC), the NE-2571 chamber is placed 25 cm from the source while the PTW-23342 chamber is placed at 17.5 cm.

### 3.2.2 Procedure

The ionization chambers are set to -300 V potential and left overnight to stabilize. This eliminates the need to pre-irradiate the chambers. The Keithley electrometer is set to collect charge at the highest accuracy and resolution. The range is set to 2 nC.

When taking a reading, the x-ray tube beam current is set to 100 μA. For each ionization chamber, the Keithley electrometer is set to read continuously for 200 points, which correspond to a collection time of roughly 100 sec. A reading is calculated by taking the difference between the first and last of the 200 data points and dividing by the collection time. The primary chamber reading is divided by the output monitor reading to give the output normalized reading.

At the start of each experiment, background noise for each chamber is measured by performing a reading with the x-ray tube off. The noise is subtracted from each subsequent measurement. After, the x-ray tube is turned on and identical readings (same kVp, same beam current, no aluminium attenuator) are done to ensure stable output. The scattered radiation is measured by blocking the collimator aperture with a thick block of lead. The scatter measurement is subtracted from attenuation measurements.

The attenuation curve is generated by taking readings with aluminium atten-
uators ranging from 0 to 1.75 mm at intervals of approximately every 0.25 mm. Because of possible changes in output over the course of the measurement, points on the attenuation curve are measured in random order to minimize systematic effects. Furthermore, despite the use of an output monitor, readings can still fluctuate over time. As such, repeated readings with no attenuation are taken frequently and readings in between are normalized to the repeated readings.

3.2.3 NE-2571 and PTW-23342 chamber response

The PTW-23342 chamber calibration report shows that the calibration coefficients for 50 kVp beams with HVLs of 0.081 and 0.22 mm Al are within 1%. Unfortunately, the report does not contain any data for 50 kVp beams with a HVL in the proximity of 0.5 mm Al (the HVL of the miniature x-ray tube). The next available calibration point is for an 80 kVp beam with HVL of 1.8 mm Al and it differs by 5%. Therefore, the chamber response for the x-ray tube spectrum is well under 5%. As such, the PTW-23342 readings are not corrected for any energy response.

The NE-2571 response curve [22] is given as function of effective energy. The curve is fitted with a line in the energy range of interest. To determine the effective energy of the beam for each attenuator thickness, spectral measurements are taken and the HVLs and effective energies calculated. The NE-2571 response is found to differ by at most 2%.

Ideally, chamber response should be calculated using Monte Carlo simulations instead of calibration curves. This is particularly important for the miniature x-ray tube because it is a kilovoltage transmission target and its spectra are unique
compared to x-ray beams used in the calibration curve.

3.2.4 Calculating HVL

After subtracting background, correcting for scatter, normalizing to the output monitor, normalizing again to repeated readings, and correcting for chamber response, the attenuation curve is fitted to a 5\textsuperscript{th} order polynomial using Mathematica. The 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs are then solved for numerically.

The main sources of error for attenuation curve measurements are output fluctuations and error in the aluminium foil thicknesses. The output fluctuation is calculated from all the repeated unattenuated readings throughout the measurement. The aluminium foil thickness error is half the smallest measurable unit on the micrometer. Because selected attenuator thicknesses are chosen to be very near the 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs, the HVL error can be simplified as the error for those points. The output fluctuation is converted to error in attenuator thickness by dividing by the slope of the curve. Adding this with the error in foil thickness gives the error in HVL.
3.3 Gafchromic film measurements

3.3.1 Materials, setup, and procedures

10×10 cm² EBT Gafchromic films are used to measure the dose distribution. Recommendations for the handling and analysis of the films are given by Devic et al [12]. Pre-irradiated films are scanned three times using a flat-bed document scanner. Films are irradiated to a maximum of 4 Gy. One film is left unirradiated to act as control. The films are scanned again 24 hours later, three times each.

30×30×6 cm³ lucite slabs are used to construct a phantom that is 30×30×30 cm³. A modified slab has a hole for insertion of the x-ray catheter and is placed in the center. Other 30×30 cm² lucite slabs are used to position the Gafchromic films at the desired distance from the source.

3.3.2 Analyzing the Gafchromic film

Analysis of the Gafchromic films is done using modified Matlab routines written by E. Poon. For each of the pre-irradiated and post-irradiated sets, the three identical scans are averaged and then corrected for scanner response. This results in two optical density (OD) images. A Wiener filter is applied to the two sets and then combined to form the net ΔOD image. Finally, a calibration curve, produced by C. Furstoss, is applied to convert net ΔOD to dose.

To compare the dose distribution with Geant4 results, which is also in the form of a 2-D dose matrix, the two matrices are registered using the 2-D correlation function in Matlab. The images are then normalized 1 cm away from the center.
Chapter 4

Geant4 Monte Carlo code
4.1 Introduction to Geant4

Geant4 is a Monte Carlo particle transport program jointly developed by CERN, SLAC, and other collaborators in the 1990s [6]. Geant4 is a major revision of Geant3 and takes an object oriented approach using C++. This makes the code highly customizable. The new object oriented program structure allows users to modify and/or add custom code without fear of affecting the rest of the program. The original purpose of Geant4 is to model high energy particle physics experiments. As such, the ability to model complex geometries, such as the detectors used at the Large Hadron Collider, is one of the major advantages offered by Geant4 [6]. Currently, Geant4 is being expanded to model ‘low energy’ (< GeV) medical physics applications [18]. Its ability to model complex geometries is suitable for simulating PET detectors and brachytherapy seeds.

Geant4 has three physics packages to choose from: \textit{G4Standard}, \textit{G4LowEnergy}, and \textit{G4Penelope}. The \textit{G4Standard} package models particles up to 100 TeV and is mainly used for high-energy physics simulations [2]. \textit{G4LowEnergy} attempts to extend the application of Geant4 to lower energies. It is the package of choice for kilovoltage medical physics applications. \textit{G4Penelope} is loosely based on the Penelope Monte Carlo code. Emphasis is placed on low energy interactions and atomic relaxation events [2]. However, \textit{G4Penelope} is no longer being maintained and it is recommended by Geant4 members that \textit{G4LowEnergy} be used instead.
4.2 Accuracy of Geant4 physics

4.2.1 Bremsstrahlung mean free path

The bremsstrahlung mean free path, MFP, is the average distance an electron travels before undergoing bremsstrahlung. Figure 4.1 [2] compares the MFP in tungsten for the three Geant4 physics options with the PEGS4 data used in EGSnrc/BEAMnrc simulations. Both G4LowEnergy and G4Penelope are 4~8 % higher than PEGS4 while the deviation of G4Standard can be as large as 15 %.

Figure 4.1: Comparison of the bremsstrahlung mean free path in tungsten (1 keV cutoff energy) between the three Geant4 physics options and the PEGS4 data used in EGSnrc. Figure taken from Poon [2].
Figure 4.2: Comparison of the three bremsstrahlung angular distribution options (Koch & Motz 2BN, Koch & Motz 2BS, and Tsai) in G4LowEnergy with experimental data for 10 keV electrons in tungsten [18].

4.2.2 Bremsstrahlung angular distribution

The G4LowEnergy package has three options for bremsstrahlung angular sampling [18]: Tsai, 2BS, and 2BN. Figure 4.2 compares the three options for 10 keV electrons in tungsten compared with experimental data. The Tsai and the Koch and Motz 2BS distributions are computationally more efficient and are adequate approximations at higher energies. However, at 10 keV, the Koch and Motz 2BN distribution is required.
### 4.2.3 Photon transport

Photon transport is primarily important outside the source. For photons up to 50 keV, the dominant interactions are photoelectric, Compton scattering, and Rayleigh scattering. Figure 4.3 compares the photoelectric mass attenuation coefficients in water and tungsten for Geant4 and the XCOM database [2]. While *G4Standard* shows up to 5% deviation from XCOM, *G4LowEnergy* and *G4Penelope* both agree within 1%.

Figure 4.4 compares the Compton mass attenuation coefficient in water and tungsten [2]. All three physics packages agree within 2% for water. In tungsten, *G4LowEnergy* provides the best fit (within 2%) for photon energies below 50 keV.

![Figure 4.3: Comparison of photoelectric mass attenuation coefficient $\tau$ between the three Geant4 physics options and XCOM in a) water and b) tungsten. Figure taken from Poon [2].]

Photon transport is primarily important outside the source. For photons up to 50 keV, the dominant interactions are photoelectric, Compton scattering, and Rayleigh scattering. Figure 4.3 compares the photoelectric mass attenuation coefficients in water and tungsten for Geant4 and the XCOM database [2]. While *G4Standard* shows up to 5% deviation from XCOM, *G4LowEnergy* and *G4Penelope* both agree within 1%.

Figure 4.4 compares the Compton mass attenuation coefficient in water and tungsten [2]. All three physics packages agree within 2% for water. In tungsten, *G4LowEnergy* provides the best fit (within 2%) for photon energies below 50 keV.
Figure 4.4: Comparison of Compton mass attenuation coefficient $\tau$ between the three Geant4 physics options and XCOM in a) water and b) tungsten. Figure taken from Poon [2].

Figure 4.5 compares the Rayleigh mass attenuation coefficient in water and tungsten [2]. Note that Rayleigh interaction is not modeled in the $G4Standard$ package. Here, there is significant deviation from the XCOM database. This observation is also seen in another paper [7], which states that the difference is due to differences between the databases (EPDL97 vs XCOM) and is not due to faulty modeling of the process.
Figure 4.5: Comparison of Rayleigh mass attenuation coefficients $\tau$ between the Geant4 Low Energy physics option and XCOM in a) water and b) tungsten. Figure taken from Poon [2].

4.3 The user code

4.3.1 Modeling the x-ray tube

For this study, Geant4 version 4.8.1p01 is used. Figure 4.6 is a wire-frame diagram of the x-ray tube model using the Geant4 HEPREP visualization option. Detailed specifications are provided by Xoft Inc. and the model used for this study is the same as that used by Rivard et al [17].

Figure 4.7 is a simplified diagram of the x-ray tube. Primary electrons are accelerated in the vacuum, impinging on the tungsten target. The x-ray tube is enclosed in an aluminium-nitride-yttrium tip. The catheter cools the tip of the x-ray tube using running water. The tip of the x-ray tube is 1 mm in diameter and 1 cm in
Figure 4.6: The Xoft Axxent miniature x-ray tube as visualized in Geant4. Only selected objects are visualized to improve visibility.

Figure 4.7: Schematic of the x-ray tube. Primary electrons are accelerated towards the x-ray target, which lines the inside of the tip. Components are not drawn to scale.
length while the cooling catheter has a diameter of 5 mm.

### 4.3.2 Bremsstrahlung splitting

As mentioned in section 2.1.1, production of bremsstrahlung photons is inefficient in the kilovoltage range. In a Monte Carlo simulation, this means that bremsstrahlung production events are rare. As a result, a greater amount of computation time is needed to simulate more primary electrons to generate sufficient numbers of photons.

One way to increase the efficiency of bremsstrahlung production is to apply the *uniform bremsstrahlung splitting* variance reduction technique as used in EGSnrc and BEAMnrc [15]. For every bremsstrahlung event, instead of sampling and generating one bremsstrahlung photon, $N$ photons, each with weights $\frac{1}{N}$, are sampled and generated. The exit energy of the electron is calculated from the first generated photon.

This same approach is used for implementation of bremsstrahlung splitting for the Geant4 user code. A *G4WrapperProcess* derived class, *userBremSplitting*, 'wraps' around *G4LowEnergyBremsstrahlung*, the default bremsstrahlung generator class. The *userBremSplitting* class instructs the program to sample and generate $N$ secondary photons each time a bremsstrahlung event occurs.

Another method to improve the efficiency of bremsstrahlung production recently published is to apply a Bremsstrahlung Cross Section Enhancement (BCSE) [5]. The bremsstrahlung cross section is increased resulting in a greater probability of photon production events occurring. Although this variance reduction technique is not used in this study, it is worth noting as a possible future enhancement to the program.
4.3.3 Latch option

The latch array is a useful feature in BEAMnrc, allowing users see where the particle has passed through or was generated. The array consists of bits (or numbers) corresponding to geometrical volumes in the simulation. Each particle would have its own latch array, detailing the particle’s history. This would be a useful feature for studying the Axxent x-ray tube, where there are many components that can contribute to the x-ray spectrum.

As such, a similar latch option is implemented for the Geant4 simulation. Each particle is represented by a $G4\text{Track}$ class object, storing the instantaneous properties of the particle (i.e. energy, position, momentum, etc.). To store the latch information, a $userTrackInformation$ class object, derived from $G4\text{VUserTrackInformation}$ class, is appended to the particle track. Thus, when the particle reaches a scoring region, the latch information from $userTrackInformation$ can be read.

The latch works as follows. The starting primary electron has no latch bits attached. A latch bit is added only when a secondary photon is generated. The latch bit corresponds to the component where the photon is created. A secondary electron generated does not have any latch bits added. However, it can inherit any latch bits already attached to parent particle.

When a particle enters the scoring region, it undergoes a latch check against latch numbers specified by the user. The user can enter an inclusive latch, where a particle is accepted if the user supplied latch is found within the particle latch bits. The other option is the exclusive latch, where a particle is accepted only if the user supplied latch is not found within the particle latch bits. The user can enter any
combination of inclusive and exclusive latches. When the user enters multiple latch requirements, the particle is checked for each user latch one at a time. Only when the particle passes all the checks is it accepted and scored by the simulation.

4.3.4 Kerma scoring for photon transport

Geant4 has a built-in primitive scorer class $G4PSDoseDeposit$ which scores dose by summing the energy deposited within a logical volume. Energy is deposited only when a photon interacts in the volume. This method of scoring is coined by Williamson as an 'analog estimator' [23]. Although the analog estimator calculates kerma while $G4PSDoseDeposit$ actually tallies dose, for the energy range concerned here (up to 50 keV), charged particle equilibrium is established within sub-mm distances and thus kerma closely approximates dose for all practical purposes [3].

Analog scoring is computationally expensive [23]. Photons passing through the scoring volume without interacting do not contribute to the kerma calculation. When modeling real-life radiation detectors, this problem is further compounded by the fact that detectors like Gafchromic films are approximately 0.2 mm thick [12], resulting in very small scoring volumes.

To improve the efficiency of scoring, one can use a 'track-length estimator' [23]. The method is based on the idea that each photon passing through a region deposits energy on average according to the mass energy absorption coefficient, $\left( \frac{\mu en}{\rho} \right)$. As a result, each photon in the region contributes to the kerma calculation, reducing the variance. There are several variants of the estimator. The one used for this study is
the ‘linear track-length estimator’ and is given by [23]:

\[ k = \sum_j w_j E_j \left( \frac{\mu_{en}}{\rho} \right)_j l_j \] (4.1)

where \( k \) is the kerma accumulated due to each photon within the scoring volume \( j \), \( w \) is the weight of the photon, \( E \) is the energy of the photon, \( \left( \frac{\mu_{en}}{\rho} \right)_j \) is the mass energy absorption coefficient corresponding to the photon energy \( E \), and \( l \) is the distance the photon traverses in the volume.

In this study, the linear track-length estimator is implemented in the userDoseScorer class which is derived from the \( G4VPrimitiveScorer \) virtual class.

### 4.3.5 Phase space (phsp) scoring

In addition to bremsstrahlung splitting, simulations of kilovoltage x-ray tubes can be further accelerated by storing the photons generated. In a simulation, the majority of the time is spent on electron production. Photon transport is relatively fast because photon production is rare and the number of interactions is less than that for electrons. By storing the phsp data, the photons can be reused for each simulation with the same beam setting.

Scoring is done by simulating the x-ray source in a vacuum. Photons are scored at the catheter/vacuum boundary and written into a binary phsp file by the userPhspScorer class. Each particle is stored as follows: energy, x y z positions, x y z momentums, number of latch bits, latch bits. Because the simulation is split into multiple jobs for the computer cluster, the output is in the form of multiple phsp files.
When the phsp file is read, the photons start at the boundary of the catheter. Each job uses a corresponding phsp file. Thus, it is important that there are as many phsp files as there are jobs.
Chapter 5

Results and Discussion

^Unless specified, all errors stated are for one standard deviation
5.1 Spectral Results

5.1.1 Spectral features

Figure 5.1: The x-ray tube spectra for 40 and 50 kVp in the forward direction. Noticeable features include characteristic peaks from tungsten, yttrium, and silver. The cadmium telluride spectrometer artifact at 26.5 keV is also observed. The spectra are normalized to unit area.

The Xoft Axxent x-ray spectra for 40 and 50 kVp beams are shown in figure 5.1. Both spectra share the same features, which are labeled in the figure. Tungsten L characteristics are at 9.7 and 11.3 keV. Yttrium K characteristics are at 14.9 and 16.7 keV. A silver K characteristic peak is seen at 22 keV. The spectra shown have been corrected for detector response. Nevertheless, the artifacts at 26.5 keV are not completely corrected for.
5.1.2 Correction for spectral artifacts

Figure 5.2: The x-ray tube spectra before and after correcting for spectrometer response. No normalization was performed.

Figure 5.2 shows the effect of correcting for detector response. Lower energy photons are removed and re-binned to higher energies. Effects of the correction are clearly visible below 10 keV. Furthermore, dips due to the CdTe K absorption edge at 26.5 and 31.5 keV are also corrected for. However, even after correction, the dip at 26.5 keV remains visible. The HVL for the corrected and uncorrected spectra are 0.440 and 0.394 mm Al respectively.

5.1.3 Source variation

Figure 5.3 compares the 1st HVL for six sources. The HVLs are calculated from spectral measurements of 40 kVp beams in the forward direction. Variation between
Figure 5.3: Comparison of the 1\textsuperscript{st} HVL calculated from measured spectrum for six sources.

Table 5.1: Table of 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energy for six sources.

<table>
<thead>
<tr>
<th>Source number</th>
<th>(40\text{ kVp})</th>
<th>(50\text{ kVp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} HVL (mm Al)</td>
<td>0.426</td>
<td>0.514</td>
</tr>
<tr>
<td>2\textsuperscript{nd} HVL (mm Al)</td>
<td>0.687</td>
<td>0.939</td>
</tr>
<tr>
<td>(E_{\text{eff}}) (keV)</td>
<td>16.5</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Sources can be up to 20\% (src 3 and src 4). Error for each HVL calculation from a spectrum (excluding source variation) is within 2\%. Setup for spectral measurements is very robust. Repeated measurements yield HVLs within 2\%, which is within the error for calculating HVL.
Table 5.1 lists the 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs and effective energy for the six sources from 40 and 50 kVp beams in the forward direction. The average 1\textsuperscript{st} HVLs are 0.45±0.04 and 0.5±0.1 mm Al for 40 and 50 kVp beams respectively. The corresponding effective energies, based on the 1\textsuperscript{st} HVLs, are 16.8±0.5 and 17.8±0.8 keV. The average 2\textsuperscript{nd} HVLs are 0.73±0.05 and 0.9±0.2 mm Al. Note that the standard deviations of both 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs due to source variation are ∼10 \% for 40 kVp while they are ∼15 \% for 50 kVp.

Comparing between the 1\textsuperscript{st} HVLs for 40 and 50 kVp beams, one can see similar changes in HVL with source number. In other words, the source variation is reflected in the same way whether for 40 or 50 kVp beams. The same can be said when comparing the 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs.

5.1.4 Source aging

Figure 5.4 compares the temporal changes in the 1\textsuperscript{st} HVLs of the same six sources from figure 5.3. For each source, three measurements are taken at different points of the source lifetime: a) before first use of the source (new), b) after about one hour of operation at 100 µA (used), and c) after about two hours of operation at 100 µA (old). The HVLs are calculated from spectral measurements taken for 40 kVp beams in the forward direction. Note that variations in HVL due to source aging can be up to 10 \%, which is larger than the error in calculating HVL (∼2 \%).

The aging process varies between sources. For example, the spectrum of src 3 changes very little with time and thus its HVL remains relatively stable. On the other hand, the spectrum of src 1 changes drastically near the end of its lifetime.
Figure 5.4: Comparison of the 1st HVL for six sources at different times.

as seen in figure 5.5. The spectrum is hardened significantly resulting in a 20% increase in HVL. Src 4 shows a slow but steady decrease in HVL over time. Yet the HVL does not necessarily change monotonically, as seen in src 6. This individualized aging process poses a serious challenge to modelling the x-ray tube. The effects due to source aging cannot be modelled if the changes in the spectra cannot be predicted.

5.1.5 Angular dependence

Figure 5.6 compares the x-ray tube spectra at three different angles: 0°, 45°, and 90°. The HVLs of the three spectra are 0.440, 0.417, and 0.316 mm Al for 0°, 45°, and 90° respectively. The main cause of the decrease in HVL with angle is due to the increased number of tungsten L-characteristic photons at 9 keV.

Figure 5.7 shows the angular dependence of the 1st HVL for three sources. Ev-
ery source shows a decrease in HVL with increasing angle. However, the angular
dependence for each source differs slightly. Src 4 exhibits the largest drop in HVL,
a 40 % decrease from 0° to 90°. Src 5 has a 30 % decrease while src 6 drops only 15
%. Furthermore, src 5 shows the spectrum changing slowly between 0° and 45° with
most of the change occurring between 45° and 90°. Src 6 shows the opposite with
most of the spectral change happening between 0° and 45°.

5.1.6 Attenuated spectra

Figure 5.8 shows the effect of the 40 kVp x-ray tube spectrum after aluminium
filtration. There is strong attenuation of the tungsten and yttrium characteristic
lines. Table 5.2 lists the 1st and 2nd HVLs and effective energies of the filtered
Figure 5.6: Angular dependence of 40 kVp x-ray tube spectrum. The arrows indicate the height of the yttrium peaks for each of the three spectra. The spectra are normalized to unit area.

Table 5.2: Table of 1st HVL, 2nd HVL, and effective energy for x-ray tube beam with aluminium filtration.

<table>
<thead>
<tr>
<th>Aluminium thickness (mm)</th>
<th>0</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
<th>1.00</th>
<th>1.25</th>
<th>1.50</th>
<th>1.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st HVL (mm Al)</td>
<td>0.440</td>
<td>0.600</td>
<td>0.742</td>
<td>0.872</td>
<td>0.995</td>
<td>1.109</td>
<td>1.213</td>
<td>1.300</td>
</tr>
<tr>
<td>2nd HVL (mm Al)</td>
<td>0.735</td>
<td>0.964</td>
<td>1.157</td>
<td>1.318</td>
<td>1.453</td>
<td>1.565</td>
<td>1.662</td>
<td>1.743</td>
</tr>
<tr>
<td>$E_{\text{eff}}$ (keV)</td>
<td>16.7</td>
<td>18.6</td>
<td>20.0</td>
<td>21.1</td>
<td>22.1</td>
<td>23.0</td>
<td>23.7</td>
<td>24.3</td>
</tr>
</tbody>
</table>

spectra. With 1.75 mm aluminium filtration, the 1st HVL increases from 0.440 to 1.300 mm Al and the 2nd HVL increases from 0.735 to 1.743 mm Al. This increases the effective energy from 16.7 to 24.3 keV.
Figure 5.7: Angular dependence of the 1st HVL for three sources.

Figure 5.8: 40 kVp x-ray tube spectrum after aluminium filtration. The spectra are normalized to unit area.
5.1.7 Choice of cutoff energy

Calculation of air kerma, which is used to determine HVL, is based on the mass energy transfer coefficient in air, \((\mu_{en}/\rho)_\text{air}\), as given in equation 2.7. This quantity increases dramatically at very low energies, going from 0.041 cm\(^2\)/g at 50 keV to 4.74 cm\(^2\)/g at 10 keV to 39 cm\(^2\)/g at 5 keV. Figure 5.9 plots the air kerma calculated from the normalized spectra for 40 and 50 kVp beams. Low energy photons in a spectrum have larger air kerma contributions and can effect HVL calculations even when they are only a small fraction of the spectrum.

To calculate HVL from spectral measurements, it is necessary to apply a low energy cutoff. Figure 5.10 shows how the 1\(^{st}\) HVL changes when different cutoff energies are used. The effects on three different spectra with different kVp and at different angles are shown. For all three plots, HVL decreases with cutoff energy.
Figure 5.10: $1^{st}$ HVL of the x-ray tube spectra as a function of cutoff energy used to calculate the HVL. Three different spectra are used to illustrate how each is sensitive to the cutoff energy.

The largest decrease is seen for the 40 kVp beam at $90^\circ$ between 9 and 10 keV and is caused by the inclusion/exclusion of tungsten L-characteristic photons which are stronger for $90^\circ$ beams (see figure 5.6). The region between 6 and 9 keV show relatively little change in HVL. The other two spectra show similar features. Thus, the cutoff energy is set to 9 keV, just below the tungsten L-lines, to include these photons.

5.1.8 Errors in HVL calculations

Equation 2.11 shows that the error for calculating HVL depends on the energy $E$, the photon count $N$, the attenuation coefficient $\mu$, and the mass energy absorption
coefficient of air \( \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{air}} \). Of the four quantities, the HVL error is dominated by the photon count component, \( \frac{\partial f}{\partial N} \) and \( N \). Other quantities are several orders of magnitude smaller. Figure 5.11 plots the contribution for the HVL error as a function of energy for 40 and 50 kVp spectra. Note that the 9 keV tungsten characteristic peak has the largest contribution.

### 5.1.9 Peak energy artifact

Examination of any of the spectra reveals that each one extends beyond the peak x-ray tube potential. The photon count falls off to background levels approximately 0.5 keV above the tube potential.

It is possible that this effect is due to error in energy bin calibration of the spectrometer. The bin positions of the calibration peaks are determined by fitting a
gaussian curve. When calculating the bin size, which should be approximately 0.1 keV, the propagated error is 0.006 keV or 6% per bin (two standard deviations). There are 90 and 190 bins from the closest calibration point (31.0 keV) to the peak energies 40 and 50 keV respectively. Thus, the error in the 40 and 50 keV energy bins are 0.54 and 1.14 keV respectively. The 0.5 keV extension of the maximum energy falls within this error.

This artifact affects the HVL by less than 0.2 % and is not significant compared to the error described in section 5.1.8.
5.2 Ionization chamber results

5.2.1 Attenuation curve

Figure 5.12: Normalized attenuation curves for 40 and 50 kVp beams in the forward direction. The beams are attenuated using aluminium foils of varying thickness.

Figure 5.12 plots the attenuation curves for the 40 and 50 kVp forward beams as a function of aluminium thickness. The NE-2571 chamber readings are corrected for background, scattered radiation, and chamber energy response. Each data point is normalized to that for the unattenuated beam. For attenuation curves using the PTW-23342, readings are corrected for background and scattered radiation.

Table 5.3 lists the 1\textsuperscript{st} and 2\textsuperscript{nd} HVLs and effective energies for the same six sources as in table 5.1 for 40 and 50 kVp beams in the forward direction. Measurements of sources 3 and 6 are done using the PTW-23342 chamber while the others are done
Table 5.3: Table of 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energy for six sources. For sources 1 to 4, two measurements were performed, one at 40 kVp and one at 50 kVp. For sources 5 and 6, two measurements were performed both at 40 kVp.

Using the NE-2571 chamber. The HVLs in table 5.3 are calculated from measured attenuation curves while those in table 5.1 are calculated from measured spectra. Errors for each 1\textsuperscript{st} and 2\textsuperscript{nd} HVL calculations (excluding source variation and aging) in table 5.3 are within 3\% and 5\% respectively.

The average 1\textsuperscript{st} HVLs are 0.48±0.04 and 0.52±0.09 mm Al for 40 and 50 kVp beams respectively. The corresponding effective energies, based on the 1\textsuperscript{st} HVL, are 17.1±0.5 and 17.9±0.5 keV. The average 2\textsuperscript{nd} HVLs are 0.8±0.1 and 1.05±0.06 mm Al respectively.

Scattered radiation, if uncorrected, becomes significant at the thick end of the attenuation curve, approximately 15\% at 1.5 mm Al for both ionization chambers. The resulting 2\textsuperscript{nd} HVL would increase by 20\%. The change in 1\textsuperscript{st} HVL is approximately 8\%.

<table>
<thead>
<tr>
<th>Source number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kVp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1\textsuperscript{st} HVL (mm Al)</td>
<td>0.438</td>
<td>0.484</td>
<td>0.435</td>
<td>0.480</td>
<td>0.482</td>
<td>0.467</td>
</tr>
<tr>
<td>2\textsuperscript{nd} HVL (mm Al)</td>
<td>0.653</td>
<td>0.744</td>
<td>0.650</td>
<td>0.786</td>
<td>0.830</td>
<td>0.821</td>
</tr>
<tr>
<td>$E_{\text{eff}}$ (keV)</td>
<td>16.7</td>
<td>17.2</td>
<td>16.7</td>
<td>17.2</td>
<td>17.2</td>
<td>17.0</td>
</tr>
<tr>
<td>50 kVp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1\textsuperscript{st} HVL (mm Al)</td>
<td>0.560</td>
<td>0.560</td>
<td>0.480</td>
<td>0.567</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2\textsuperscript{nd} HVL (mm Al)</td>
<td>1.095</td>
<td>1.097</td>
<td>0.970</td>
<td>1.044</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\text{eff}}$ (keV)</td>
<td>18.1</td>
<td>18.1</td>
<td>17.2</td>
<td>18.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2.2 Comparison with spectral results

Figure 5.13: Source by source comparison of the 1st HVL for six sources from spectral measurements and ionization chamber measurements. Sources 3 and 6 were measured using the PTW-23342 ionization chamber while the others were measured using the NE-2571 chamber. For sources 5 and 6, two ionization chamber measurements were performed.

Figure 5.13 takes the results shown previously (measured spectra from section 5.1.3 and measured attenuation curves from section 5.2.1) and compares, for each source, the 40 kVp 1st HVLs calculated. Note that two measurements were done for src 5 and src 6. With the exception of the second src 5 measurement, the HVLs from spectra and ionization chamber measurements agree to within 10 %. The average difference for calculating HVL is 6 %. Dropping the second src 5 measurement reduces the difference to 4 %.

Figure 5.14 plots the average 1st HVLs, 2nd HVLs, and effective energies for the
Figure 5.14: Comparison of the average 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energies from measured spectra and measured attenuation curves. The scale for HVLs is on the left while the scale for effective energies is on the right.

six sources, again comparing the two HVL calculation methods. Unlike the error bars in figure 5.13 which represent errors in calculating HVL from the spectra, error bars in figure 5.14 represent the standard deviation of the six sources. Because of the large error in each data set, there is no statistically significant difference between HVLs obtained from spectral measurements as opposed to ionization chamber measurements.

Also, note that the effective energies do not change significantly between the 40 and 50 kVp beams (17 and 18 keV respectively). Even after 1 mm Al filtration, the effective energies are 22 and 24 keV, respectively.
5.2.3 Angular dependence

Figure 5.15: 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energies for src 7 beam at 90\(^\circ\) from measured spectra and measured attenuation curves. The scale for HVLs is on the left while the scale for effective energies is on the right.

The decrease in HVL with increasing angle is also observed in ionization chamber measurements. Figure 5.15 plots the 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energies for src 7 measured at 90\(^\circ\). Except for the 2\textsuperscript{nd} HVL at 50 kVp, the HVLs from spectra and attenuation curves match within the stated error. From attenuation curve measurements, the 1\textsuperscript{st} HVLs at 90\(^\circ\) for 40 and 50 kVp are 0.378 and 0.430 mm Al respectively. The average 1\textsuperscript{st} HVLs for 0\(^\circ\) attenuation curve measurements are 0.48±0.04 and 0.52±0.09 mm Al. Although the difference is not statistically significant due to source variation errors, the decrease in HVL with angle from attenuation curve measurements agrees with the spectral measurements in section 5.1.5.
5.2.4 Output stability

Figure 5.16: The x-ray tube output for two sources as measured by the output monitor during attenuation curve measurements. For each source, two attenuation curve measurements are performed with a 15 minute break in between.

Figure 5.16 plots the output monitor readings during attenuation curve measurements for sources 5 and 6. The x-ray was in operation continuously except between 34 and 49 minutes when it was turned off. When the source is turned on again for the second measurement, the x-ray tube output changes and may take time to stabilize.

When the primary chamber is normalized to the output monitor, readings have a 0.5 % variation. However, the output monitor can not compensate for fluctuations like those seen between 50 and 60 minutes. The variation after normalizing is 2 %, indicating either a change in beam quality or spatial distribution.
5.2.5 Reproducibility

Two identical attenuation curve measurements are performed each for sources 5 and 6. As shown in figure 5.13 and table 5.3, source 6 yields similar results while the two attenuation curves for source 5 differ greatly. The change in output as seen in figure 5.16 suggests that the source output is not stable, possibly accounting for the difference in results. The spectral measurements in figure 5.4, however, show very little change. The second attenuation curve measurement is performed between ‘used’ and the ‘old’ spectra, which show only a 2 % change.

The problem concerning reproducibility of attenuation curve measurements is that the source lifetime is only 2 hours using a beam current of 100 μA. Each measurement requires 30 to 45 minutes, a significant fraction of the x-ray tube lifetime. During that time, the x-ray tube output can change drastically, as seen for source 5. Therefore, the HVLs from attenuation curve measurements are not reproducible.

Spectral measurements, on the other hand, are more reliable. Each measurement only requires two minutes at very low beam currents (5 μA). Repeated spectral measurements are within 2 %.

5.2.6 NE-2571 vs PTW-23342

The initial concern with the NE-2571 chamber is that the L-line tungsten characteristics at 9 keV (as shown in figure 5.6) would be filtered by the chamber wall, resulting in biased measurements. The wall of the NE-2571 chamber is made of low density graphite (1.7 g/cm³) approximately 1~1.5 mm thick. The approximate
transmission probabilities of a primary photon beam are:

\[6keV \rightarrow 14\%\]
\[8keV \rightarrow 37\%\]
\[10keV \rightarrow 61\%\]

The window of the PTW-23342 chamber is made of 0.03 mm Beryllium, allowing for transmission of these low energy photons. On the other hand, the energy region (6∼10 keV) where the transmission probability changes for the NE-2571 is a concern for these 9 keV characteristic photons. Thus, the attenuation curves from the two chambers may differ.

The magnitude of the effect is illustrated by the dependence of the spectrum derived HVL on cutoff energy (figure 5.10). Thus, it is expected that the HVL measured from the NE-2571 chamber to be greater. However, as shown in figure 5.13, any possible systemic effect is overshadowed by the variation between sources.
5.3 Geant4

5.3.1 Photon production compared with BEAMnrc

Figure 5.17: Comparison of x-ray production for BEAMnrc, BEAMnrc without electron impact ionization, and Geant4. Simulations are for 90 keV electrons incident on a 10 μm tungsten slab. The arrows indicate the height of the characteristic peaks. The spectra are normalized to unit area.

To compare photon production between BEAMnrc and Geant4, simulations are done with 90 keV electrons incident on a 10 μm tungsten slab (the same material as the miniature x-ray tube target). Figure 5.17 plots the normalized spectra for BEAMnrc with electron impact ionization (eii), BEAMnrc without eii, and Geant4. The continuous bremsstrahlung spectra of the three simulations match extremely well. Tungsten L-characteristic peaks are observable at 9 keV and K-characteristic peaks at 59 and 68 keV. As expected, the characteristic peaks for BEAMnrc with eii
Figure 5.18: Comparison of x-ray production for BEAMnrc, BEAMnrc without electron impact ionization, and Geant4. Simulations are for 50 keV electrons incident on a 80 μm yttrium slab. The arrows indicate the height of the characteristic peaks. The spectra are normalized to unit area.

are stronger than those without eii. However, the peak heights for Geant4 simulations are similar to the BEAMnrc spectrum without eii. This suggests that the Geant4 implementation of electron impact ionization may not be correct.

Because yttrium contributes the largest number of characteristic photons to the x-ray tube spectrum, it would be more relevant to investigate the differences between BEAMnrc and Geant4 for yttrium, instead of tungsten in figure 5.17. Figure 5.18 shows the normalized spectra produced from 50 keV electrons incident on a 80 μm yttrium slab. The characteristic peak at 14.9 keV clearly shows the difference between BEAMnrc, BEAMnrc without eii, and Geant4, with the BEAMnrc peak 6 times stronger than that of BEAMnrc without eii and Geant4.
Figure 5.19: Comparison of x-ray production for BEAMnrc, BEAMnrc without electron impact ionization, and Geant4. Simulations are for 50 keV electrons incident on a 500 μm yttrium slab. The arrows indicate the height of the characteristic peaks. The spectra are normalized to unit area.

Figure 5.19 shows the normalized spectra from 50 keV electrons incident on a much thicker 500 μm yttrium slab. This time, the discrepancy between the simulations are smaller, only 50%. As previously discussed in section 2.1.2, characteristic photons from the photoelectric effect dominates those from electron impact ionization in thick targets. The smaller difference between BEAMnrc and BEAMnrc without eii in figure 5.19 compared to 5.18 confirms that photoelectric effect contribution is surpassing that of eii. Furthermore, from the similarities of the Geant4 spectra with those of BEAM without eii, one can claim that the Geant4 code does not have eii properly implemented.

Fortunately, the miniature x-ray tube target is sufficiently thick (0.7 μm target
Figure 5.20: Comparison of x-ray production for BEAMnrc, BEAMnrc without electron impact ionization, and Geant4. Simulations are for 50 keV electrons incident on a 0.7 μm tungsten slab followed by a 0.3 mm yttrium slab. The arrows indicate the height of the characteristic peaks. The spectra are normalized per incident particle with the exception of Geant4 Normalized which is normalized to the BEAMnrc spectrum.

plus 0.3 mm tip) such that electron impact ionization is not a significant contributor of photons. Figure 5.20 compares BEAMnrc and Geant4 for a simplified model of the miniature x-ray tube, a 0.7 μm thick tungsten slab followed by a 0.3 mm yttrium slab. Three of the spectra (BEAMnrc, BEAMnrc without eii, Geant4) are normalized to per incident particle. The characteristic peaks match well, as expected. The bremsstrahlung production is slightly greater for Geant4. However, if normalized to the area of the BEAMnrc spectrum, the two spectra are very similar with 1st HVLs of 0.705 and 0.699 mm Al for BEAMnrc and Geant4 respectively.
### 5.3.2 Comparison with experiments

![Comparison of spectra](image)

Figure 5.21: Comparison of the average spectrum from experiments and Geant4 spectra using the *G4LowEnergy* and *G4Penelope* physics options. Arrows indicate the height of the characteristics peaks. The spectra are normalized to unit area.

Figure 5.21 compares the average spectrum from forward direction spectral measurements to Geant4 spectra using the two low energy physics options: *G4LowEnergy* and *G4Penelope*. The main difference between the options is the missing tungsten L-lines in the *G4LowEnergy* spectrum. Aside from that, the spectra are almost identical with 1\textsuperscript{st} HVLs of 0.521 and 0.520 mm Al respectively. The average experimental spectrum matches the simulations well with a 1\textsuperscript{st} HVL of 0.529 mm Al.

Note that the characteristic peaks for the experimental spectrum are broadened while the Geant4 spectra have very tall peaks. Comparing the experimental, *G4LowEnergy*, and *G4Penelope* spectra, the areas under the yttrium K-\(\alpha\) character-
Figure 5.22: Comparison of the average 1\textsuperscript{st} HVL, 2\textsuperscript{nd} HVL, and effective energy from all three methods: measured spectra, measured attenuation curves and Geant4 Monte Carlo simulations. The scale for HVLs is on the left while the scale for effective energies is on the right.

The characteristic peak at 14.9 keV are 0.032±0.006, 0.032±0.001, and 0.034±0.001 respectively.

Figure 5.22 displays the average 1\textsuperscript{st} HVLs, 2\textsuperscript{nd} HVLs, and effective energies from figure 5.14 in section 5.2.2 and compares them to the Geant4 \textit{G4LowEnergy} results. The 1\textsuperscript{st} HVLs and the effective energies (which are calculated from 1\textsuperscript{st} HVLs) from Geant4 spectra, are within 5 \% of measurements. For the 2\textsuperscript{nd} HVL, however, the Geant4 spectra are within 5 \% of spectral measurements and within 10 \% of attenuation curve measurements. The attenuation curve measurements are also consistently higher. However, because of the large errorbars, all three sets of data agree within one standard deviation.
5.3.3 Source of photons

Figure 5.23: Contribution to the x-ray tube spectrum from different parts of the source. The three spectra are normalized to the 'total' spectrum.

In Geant4 simulations, latch bits are attached to secondary photons. These latches contain information on where the photons are generated. Figure 5.23 plots the complete x-ray tube spectrum compared to the spectra contributed by the tungsten target and the yttrium tip. The geometry of the tip and target is shown in figure 5.24.

Photons generated in the target constitute the majority of the bremsstrahlung photons, due to the high atomic number of tungsten. 87% of the total spectrum is generated in the target. The tip contributes 7% of the total spectrum. All other components have insignificant contributions of less than 1%. For the simulations, the latch bits are set as exclusive bits, meaning the 'target' spectrum contains photons
Figure 5.24: Two scenarios for generating yttrium characteristic photons by creating vacancies in the tip. 

a) the primary electron travels through the target and undergoes an electron impact ionization in the tip. 
b) the electron undergoes bremsstrahlung production in the target. The bremsstrahlung photon then undergoes a photoelectric effect in the tip. The dimensions are not to scale.

generated only in the target.

However, approximately 5% of the photons are unaccounted for. This can be seen in figure 5.23. The yttrium K-characteristic at 15 keV should be generated at the tip, which is the only component with yttrium. The yttrium characteristic lines in the 'tip' spectrum is only a small fraction of the total characteristic peaks.

In fact, the missing yttrium characteristic photons have latch bits from both the target and the tip and account for the remaining 5% of the total spectrum. These photons have two latch bits because they are generated in a two step process as shown by the b) electron in figure 5.24. The primary electron undergoes bremsstrahlung
production in the target, creating a photon which has a latch bit of the target. The photon then undergoes a photoelectric effect in the tip, generating a vacancy in the tip. The characteristic photon which results would have a latch bit of the tip and also inherits the latch bit of the target.

The yttrium characteristic photons seen in the 'tip' spectrum have only a latch bit of the tip. The a) electron in figure 5.24 illustrates how these photons are created. The primary electron passes through the target and collides with an orbital electron, undergoing electron impact ionization. The resulting vacancy results in a characteristic photon which has a latch bit of the tip.

The results from the latch bits suggests that the majority of the yttrium characteristic photons are generated via the photoelectric effect. Note that Compton scattering is another means of generating vacancies. However, as shown in figure

Figure 5.25: Photon cross sections for yttrium atoms \((Z = 39)\) [9].
5.25 [9], the photoelectric cross section for yttrium atoms \((Z = 39)\) is at least two orders of magnitude larger than the Compton cross section.

### 5.3.4 Target thickness

![Figure 5.26: Comparison of x-ray tube spectra with various target thicknesses. Arrows indicate the height of the characteristics peaks. The spectra are normalized to unit area.](image)

Initially, it was suspected that the source variations and aging effects in the x-ray spectrum are primarily due to changing target thickness. This suspicion is based on the fact that 87% of the spectrum is generated in the target. Figure 5.26 compares spectra with different target thicknesses. The target thickness is defined at the central axis running parallel to the source, as shown in figure 5.27. The nominal target thickness is 0.7 μm. The spectra for 1.4, 0.7, and 0.35 μm target thicknesses
are very similar with 1\textsuperscript{st} HVLs of approximately 0.51±0.01 mm Al. Only when the target is very thin does the spectrum significantly differ, with a HVL of 0.447 mm Al.

Thus, it is uncertain whether changing target thickness is the cause of the variation in spectra. It is difficult to judge whether a ten-fold change in thickness can occur in a target that is only microns in thickness.

### 5.3.5 Beam width

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>0</th>
<th>0.3</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} HVL (mm Al)</td>
<td>0.556</td>
<td>0.526</td>
<td>0.532</td>
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<tr>
<td>2\textsuperscript{nd} HVL (mm Al)</td>
<td>0.995</td>
<td>0.962</td>
<td>0.964</td>
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</table>

Table 5.4: Effect on 1\textsuperscript{st} and 2\textsuperscript{nd} HVL due to beam width.

The primary electron beam is modeled as a uniform circular beam. Table 5.4
shows the effect on HVLs with beam radius. Simulations are for 50 kVp beams and photons are scored over $4\pi$ solid angle. A beam radius of 0 mm represents a pencil beam while the beam radius of 0.8 mm is the largest possible beam for the x-ray tube geometry. 0.3 mm is the nominal radius used in most simulations and corresponds to the beam covering the hemispherical part of the target (see figure 5.24). HVLs for the entire range of radii are within 5 %.

### 5.3.6 Angular dependence

![Angular dependence of x-ray tube spectrum](image.png)

Figure 5.28: Angular dependence of x-ray tube spectrum using the *G4LowEnergy* physics option. The arrows indicate the height of the yttrium peaks for each of the three spectra. The spectra are normalized to unit area.

Figure 5.28 compares the Geant4 simulated spectra at three difference angles: $0^\circ$, $45^\circ$, and $90^\circ$. Unlike the measured spectra in figure 5.6, there is no significant
change in the spectrum with angle. The increase in tungsten L-characteristic photons observed in measured spectra is not shown in the Geant4 results. The $G4LowEnergy$ physics option is used. 1$^{st}$ HVLs are 0.522, 0.551, and 0.550 mm Al for 0°, 45°, and 90° respectively. Simulations using the $G4Penelope$ physics option also yields similar results. 1$^{st}$ HVLs are 0.489, 0.508, and 0.520 mm Al. In both physics options, Geant4 simulated spectra hardens with angle, opposite to measured spectra. The reason for this discrepancy between experiments and simulations is unknown.
5.4 2D dose distribution

5.4.1 Comparison with Geant4

Figure 5.29 compares measured dose distributions using EBT Gafchromic film and Geant4 simulated results, using relative contours. The x-ray tube is placed in lucite and is positioned parallel to the plane of measurement. Simulations were done with source-to-scoring-region distances of 1 cm and 1.5 cm. The normalization is done 1 cm from the center of the distribution. The difference in most regions is within 5%. However, areas behind the source (bottom of the graphs) show significant differences of greater than 10%. The cause is unknown.

5.4.2 Energy dependence of EBT Gafchromic film

<table>
<thead>
<tr>
<th>x-ray beam (kVp)</th>
<th>effective energy (keV)</th>
<th>relative response (±0.037)</th>
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</thead>
<tbody>
<tr>
<td>50</td>
<td>28</td>
<td>0.923</td>
</tr>
<tr>
<td>75</td>
<td>32.5</td>
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</tr>
<tr>
<td>100</td>
<td>39</td>
<td>0.930</td>
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<tr>
<td>125</td>
<td>53</td>
<td>0.929</td>
</tr>
<tr>
<td>150</td>
<td>68</td>
<td>0.928</td>
</tr>
</tbody>
</table>

Table 5.5: Relative energy response of EBT Gafchromic film to a range of x-ray beams. Data taken from Butson et al [26].

EBT Gafchromic films are known to be weakly energy dependent [11]. Table 5.5 lists the relative response of EBT over a range from energy from 50 to 150 kVp [26]. Within the range of effective energies from 28 to 68 keV, the dose response does not
Figure 5.29: Comparison of normalized dose contours for Gafchromic film measurements (solid) and Geant4 results (dotted). The x-ray tube is placed parallel to the plane of measurement at distances of 1 cm (top) and 1.5 cm (bottom).

change more than 1%. However, energy response of EBT for the miniature x-ray tube is unknown.
The Xoft tube has an effective energy of 16~18 keV, much lower than the 28 keV effective energy point in table 5.5. Due to attenuation in the lucite, the effective energy of the x-ray tube spectrum ranges from 18 to 25 keV, after 1 and 5 cm lucite attenuation respectively. From the relatively stable response between 28 to 68 keV effective energy, one can hope that the response for the miniature x-ray tube does not change significantly. This is an area that requires further study and will be addressed in future research.
Chapter 6

Conclusion
6.1 Summary of results

<table>
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<th></th>
<th>90 deg</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>spectra</td>
<td>Geant4</td>
<td>spectra</td>
</tr>
<tr>
<td>40 kVp</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; HVL</td>
<td>0.45±0.04</td>
<td>0.45±0.01</td>
<td>0.37±0.02</td>
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<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; HVL</td>
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<td></td>
<td>E&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>16.8±0.5</td>
<td>16.8±0.2</td>
<td>15.7±0.1</td>
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<tr>
<td>50 kVp</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; HVL</td>
<td>0.53±0.08</td>
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<tr>
<td></td>
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<td>0.8±0.1</td>
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<tr>
<td></td>
<td>E&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>17.8±0.8</td>
<td>17.7±0.1</td>
<td>16.4±0.2</td>
</tr>
</tbody>
</table>

Table 6.1: 1<sup>st</sup> HVLs, 2<sup>nd</sup> HVLs, and effective energies E<sub>eff</sub> obtained from spectral measurements, attenuation curve measurements, and Geant4 simulations. Values for HVL are in mm Al and values for E<sub>eff</sub> are in keV.

Table 6.1 lists the 1<sup>st</sup> HVLs, 2<sup>nd</sup> HVLs, and effective energies of the miniature x-ray tube. Spectral and attenuation curve measurements at 0° are averaged over 6 sources<br>1. The measurements at 90° are determined using only one source 2.

HVLs in the forward direction calculated from spectra, attenuation curves and Geant4 simulations agree within one standard deviation, with the exception of the 2<sup>nd</sup> HVLs at 50 kVp agreeing within two standard deviations. This suggests that the measurements are reliable and that the Geant4 simulation can adequately model the beam in the forward direction. However, variations between sources and source aging result in errors ranging from 10 to 20 %, making it difficult to determine systematic errors in the measurements or the simulations (e.g. NE-2571 chamber response).

Spectral measurements show an increase in tungsten L-characteristic photons (9 keV) with angle. HVLs of the 90° beams from both spectral and attenuation curve

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1Errors are calculated from the standard deviation of the 6 sources
2Error calculations are described in sections 2.3.3 and 3.2.4
measurements are significantly lower. However, Geant4 spectral results do not show any increase in L-characteristic photons and the HVLs remains relatively constant. The reason why Geant4 differs from the measurements is unknown.

The x-ray spectrum hardens significantly with attenuation. The 1st HVL increases from 0.440 to 0.872 mm Al with 0.75 mm of aluminium attenuation. The effective energy increases from 16.7 to 21.1 keV. After 1.50 mm of aluminium attenuation, most of the 9 and 15 keV characteristic photons have been attenuated.

Fluctuations in the x-ray tube output can have a significant impact on the reproducibility of attenuation curve measurements. The HVLs of two measurements can differ by as much as 20 %, even though spectral measurements show little change as the source ages. A sudden and drastic change in the output monitor reading is an indication that the measurement may be unreliable.

A Geant4 Monte Carlo code has been written and tested against the BEAMnrc code. The Geant4 code lacks the electron impact ionization implementation, which results in less characteristic photon production compared with BEAMnrc simulations. However, the x-ray tube target and tip are thick enough that characteristic photons are produced mostly via the photoelectric effect. As a result, Geant4 x-ray production for a simplified x-ray tube geometry is comparable with BEAMnrc.

Geant4 simulations show that 87 % of the photons are produced in the tungsten target. 7 % of the photons are produced in the tip encapsulating the x-ray tube. 5 % of the photons result from a two-stage process. Primary electrons undergo bremsstrahlung interactions and the resulting photons undergo photoelectric interactions. These 5 % of the photons comprise the majority of the yttrium characteristic
photons in the x-ray tube spectrum.

According to Geant4 simulations, the x-ray spectra are relatively insensitive to changes in primary electron beam and the target thickness. Only with extreme change does the 1st HVL change by 10 %, which roughly corresponds with the HVL variation between sources. However, it is uncertain whether these extreme changes in geometry are realistic. As such, the cause of the variation in spectra is yet unknown.

2-D dose distributions are compared between EBT Gafchromic film measurements and Geant4 simulations. The relative dose distribution in most areas match within 10 %. However, there is significant deviation at 180°.
6.2 Future work

The discrepancy between spectral measurements and Geant4 results for the 9 keV characteristic photons have to be determined. These photons are particularly important for the x-ray beam at 90°. There are hypotheses that can be investigated. One possible issue is beam divergence. A divergent beam would result in photon production in the sides of the x-ray tube. Another consideration is that the 9 keV characteristic photons are not from the tungsten target. The small number of tungsten L-characteristic photons in both Geant4 and BEAMnrc simulations suggests the problem is not in the production of tungsten characteristic photons.

Source variation and aging are the primary sources of HVL measurement errors for both spectra and attenuation curves. Thus, it is difficult to compare HVL values more accurately. The standard deviation of 1st HVLs for spectral measurements is 10 %. This is the same for attenuation curve measurements. On the other hand, if the HVLs are compared on a source by source basis, the average difference between 1st HVLs is 6 %. Thus, attenuation curve measurements that are completely corrected for output fluctuations would allow for better comparisons between HVL measurements.

The energy response of EBT Gafchromic film for the miniature x-ray tube needs to be studied. Currently, it is only assumed that the energy response is nearly uniform as the x-ray beam hardens in several cm of lucite.

The deviation between Gafchromic film measurements and Geant4 simulations for 2-D dose measurements needs to be corrected for. It is not certain whether this difference is due to poor modeling aft of the source or is related to the discrepancy of the spectra at 90°. After this problem is solved, the next step would be to compare
simulations and measurements in terms of absolute dose distribution.
Bibliography


