2005

Neutron fluence measurements of the Siemens Oncor linear accelerator utilizing gold foil activation

Todd M. Hill
Medical University of Ohio

Follow this and additional works at: http://utdr.utoledo.edu/theses-dissertations

Recommended Citation
http://utdr.utoledo.edu/theses-dissertations/1433

This Thesis is brought to you for free and open access by The University of Toledo Digital Repository. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of The University of Toledo Digital Repository. For more information, please see the repository's About page.
Neutron Fluence Measurements of the Siemens Oncor Linear Accelerator Utilizing Gold Foil Activation

Submitted by
Todd M. Hill

In partial fulfillment of the requirements for the degree of Master of Science in Biomedical Sciences

Date of Defense:
December 14, 2005

Major Advisor
E. Ishmael Parsai, Ph.D.

Academic Advisory Committee
Michael Dennis, Ph.D.
John Feldmeier, D.O.

Dean, College of Graduate Studies
Keith K. Schlender, Ph.D.
Neutron Fluence Measurements of the Siemens Oncor
Linear Accelerator Utilizing Gold Foil Activation

Todd M. Hill

Medical University of Ohio

2005
DEDICATION

This work is dedicated to my wonderful wife, Melody, and children Aaron, Miranda, and Leah.
ACKNOWLEDGEMENTS

Thank you to David Followill, Ph.D., of M.D. Anderson in Texas for agreeing to help out with the cross calibration of the gold foils;

Steven Kry, M.S., of M.D. Anderson in Texas for the actual work involved with cross calibration of the gold foils and for providing your much-needed insight;

Andrew Schneider, Ph.D., for pointing me in the right direction at the start of this work and for keeping me going when the research was not;

Blanchard Valley Regional Health Associates in Nuclear Medicine for the use of their Multi-channel Analyzer during the measurement phase of the research; and to Tiffin Mercy Hospital Radiation Therapy Center Associates in Radiation Oncology for the use of the Linear Accelerator.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedication</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Literature</td>
<td>12</td>
</tr>
<tr>
<td>Materials</td>
<td>16</td>
</tr>
<tr>
<td>Methods</td>
<td>17</td>
</tr>
<tr>
<td>Results</td>
<td>25</td>
</tr>
<tr>
<td>Discussion</td>
<td>29</td>
</tr>
<tr>
<td>Conclusion</td>
<td>35</td>
</tr>
<tr>
<td>Summary</td>
<td>36</td>
</tr>
<tr>
<td>References</td>
<td>37</td>
</tr>
<tr>
<td>Abstract</td>
<td>43</td>
</tr>
</tbody>
</table>
INTRODUCTION

Siemens Medical Systems has recently introduced a new high-energy linear accelerator into service called Oncor (Figure 1). The machine is the newest version following the Primus Accelerator and capable of producing high energy x-rays of 6 MV and 18MV. It has a collimating system consisting of two lead upper jaws and an 82 leaf multileaf collimator (MLC) for the lower jaws. With this unit, the MLCs are the primary collimator and are used to form the blocked fields and the segmented fields during intensity modulated radiation therapy (IMRT). This machine is capable of producing high-energy photons in excess of 10MV and a neutron study was performed in order to characterize the neutron fluence.

The significance of neutron radiation from the accelerator head is that neutrons deliver an extra and undesired dose to the patient and may travel through the poorly shielded treatment barriers to controlled and uncontrolled radiation areas where dose can be delivered to anyone in the vicinity. This neutron dose poses a problem for radiation therapy patients due to the fact that the neutron dose is primarily delivered to the whole body. Furthermore, the biological effect of neutron exposure is between 10 and 20 times greater than for photons, thus increasing the damage caused to healthy tissue. This may lead to an increased risk of secondary effects such as tumor recurrence or secondary malignancies. This dose has been measured to add an additional 1% of the peripheral dose to the patient (NCRP 79) for 25 MeV x-rays, and also delivers an increased dose to the treatment area due to in-beam contamination.
The increased dose from neutrons generally has been regarded as negligible, but as the utilization of high-energy x-rays for IMRT becomes more prevalent, the increase in this dose could become significant. The reason is two-fold.

First is the fact that the number of monitor units required to complete an IMRT treatment as compared to conventional conformal radiotherapy is approximately two to three times. Furthermore, with the advent of IMRT, it has been possible to increase the tumor dose by 5-10%, thus increasing the potential neutron dose even further.
Neutrons are generally produced in the head of linear accelerators from the nuclear reactions that arise when the primary high-energy x-rays are incident upon the walls of the vacuum chamber and wave-guide, electron target, collimators, flattening filters, and head shielding (Figures 2 and 3). This results in neutrons being emitted from the area of the head and interacting with other materials. These other interactions can result in secondary neutron production or bremsstrahlung radiations, further increasing contamination in the vicinity of the accelerator and treatment room.

Figure 2. Ghosted View of Siemens Oncor Linear Accelerator (Hulsey)
The production of neutrons depends highly on the photoneutron production cross-section of the materials with which they interact. The cross-section for neutron production determines the probability of a reaction occurring (Figure 4). It is small at low energies and increases to a maximum value as the energy increases. As the photon energy increases further, the cross-section begins to taper off and becomes small again around 22 MeV. The peak in the cross-section plot is characteristic of resonance reactions and is termed the giant resonance; whose full width at half max for lead (Pb) is approximately 11 to 15 MeV with a peak at approximately 13 MeV. Figure 4 also shows the start of neutron production at 10 MeV.
Figure 4. The Photonuclear Production ($\gamma$, n) Cross Sections for $^{208}$Pb Showing the Peak at Approximately 13 MeV (Data taken from NCRP 79, 1984)

Figure 5 is the same plot as Figure 4, but shows the relative number of photons for the upper end of an 18MV photon spectrum. It was obtained from the model of an 18MV photon beam from a Philips Pinnacle treatment planning system. It is interesting to note that the relative number of photons in the high-energy range is significantly lower than the low to medium energy range, which makes up most of the spectrum. Nevertheless, the photoneutron cross section is high enough in this range that neutron production is significant to warrant measurement.
Figure 5. Plot of Photonuclear Production ($\gamma$, n) Cross Sections for $^{208}$Pb Superimposed with the Relative Number of Photons for an 18MV Beam

The resonance of the photonuclear interaction is equal to $60\frac{NZ}{A}$ (MeV – mbarns) where $N$ is the number of neutrons, $Z$ is the number of protons (atomic number) and $A$ is the sum of $N$ and (mass number) $Z$ (NCRP 79). This is referred to as the strength of the giant resonance and demonstrates that as $N$ and $Z$ increase, so does the probability of neutron production.

When photons with energy greater than 10 MV strike high Z materials such as tungsten and lead (approximately 7 MeV threshold), the ($\gamma$, n) reaction that occurs transfers much of the high energy from the photon to the atomic nucleus. The nucleus remains in this excited state momentarily, but soon releases its excess energy by the ejection of a neutron, decreasing the mass number by one. Unlike bremsstrahlung
however, these neutrons are produced approximately isotropically and leave the source in all directions. However, there is little attenuation of the high-energy neutrons due to the very small capture cross sections of the materials making up the head (McCall, 1979). Inelastic and elastic collisions do occur, but the inelastic collisions are the predominant method of energy loss. On the other hand, the elastic scattering primarily results in an increased path length for the neutrons. This combination of scattering events results in a small to medium decrease in energy, but contrasting photon attenuation, the total number of neutrons generally remains constant. After the neutrons leave the head, they interact with other materials, such as the concrete walls and are further scattered creating the secondary low energy, and thermal neutrons.

Neutrons are divided into two categories as determined by their energy. Slow neutrons are those neutrons with energy less than 0.5 eV. Consequently, this energy corresponds to the increase in absorption cross section of cadmium beginning at 0.5 eV (the cadmium cutoff energy). This is significant because cadmium metal is used as a filter during neutron measurements to remove the slow neutrons. This filtering is facilitated due to the high absorption of neutrons by cadmium in this low energy range. As the energy increases above 0.5 eV, the absorption abruptly decreases and the higher energy neutrons can pass through with relatively little interaction. This allows only the high-energy neutrons to be detected and provides a basis for energy separation.

Thermal neutrons are generally considered as having energies less than 0.025 eV. If one uses the classical kinetic energy equation, $KE = \frac{1}{2} MV^2$ we find that the velocity of the neutron is 2200 m/s or about 4000 miles per hour. This velocity ensures that any given neutron will have sufficient energy to be captured by the shielding material and no
free neutrons will be present at the time of “beam-off.” Also, given the half-life of a free neutron of 10.4 min, it is safe to say that if any neutrons do happen to be “stopped” in the room, they will soon decay and the room will be neutron-free.

The energy distribution of the neutrons produced by the photonuclear process can be quite complex, but the mean energy of the neutron spectrum produced in the head and treatment room is approximately a few MeV (Ongaro, 2000). The AAPM Report 19 lists the primary energy of the neutrons to be 1.8, 2.1, 2.2, and 2.4 MeV for 15, 20, 25, and 30 MV x-rays. Since the Oncor is an 18 MV machine, the value of 1.97 MeV was used for the primary (average) energy of the neutron emission.

Similar to gamma rays, neutrons are particles that carry no charge and do not undergo the effects of the Coulomb force that is the attractive and repulsive force felt when two charged particles come in the vicinity of each other. This lack of interaction makes it impossible to directly detect neutrons in the same way electrons are detected. Therefore, that detection needs to be accomplished by some other fashion. Several methods exist for the detection of neutrons. Of those methods, only three are generally used in radiation therapy. They are (1) the Bonner sphere, an active detection device, (2) the passive moderated gold foil method, and (3) the superheated drop Bubble detector which can be either passive or active.

The Bonner sphere is a moderated active detector system that utilizes several polyethylene spheres of different sizes with LiI scintillating detectors placed at the center. The spheres are designed to thermalize the neutrons before they reach the detector. By using several different sizes of moderators, it is possible to discriminate between different energy neutrons. The large spheres slow the highest energy neutrons down to the thermal
range while the smallest spheres slow only the low energy neutrons. The result is that the small spheres will not detect the high-energy neutrons and the low energy neutrons will be too slow to be detected by the large sphere. As the neutron interacts with the LiI scintillator, the lithium atom undergoes a \((n, \alpha)\) reaction. This alpha particle then transfers its energy to the LiI crystal, which then acts like a traditional scintillation detector in which the activity can be counted electronically. Another version of the Bonner sphere uses a traditional \(^3\)He proportional counter in which the resultant alpha particles are collected directly by a center electrode, much like a cylindrical ion chamber. This spectrum allows one to determine the dose from a wide range of neutron energies.

The moderated gold foil method uses a hydrogenous material (polyethylene) to reduce the fast neutrons in the room to thermal energies that can activate a gold foil placed at the center. The response of the system is dependent on the size and shape of the moderator, but a 15 cm cylinder covered in cadmium has been shown to provide consistent response per unit fluence over different energies (NCRP 79). As the system is exposed to a neutron fluence, the gold foil becomes activated. The process is illustrated as follows:

\[
\text{Au-197} + n \rightarrow \text{Au-198, (}\gamma, n\text{)}
\]

The activated gold (Au-198) has a half life of 2.7 d and decays to Hg-198 by beta decay (1.3 MeV) and emitting a 412 keV photon (95.5%):

\[
\text{Au-198} - \beta^- \rightarrow \text{Hg-198} + \gamma
\]
Either the beta or the photon can be detected depending on the type of counting system used. Both the beta detection and photon generally consists of a single channel analyzer with a pancake probe or a NaI scintillation detector facilitating to windowing of the interested energy peak. In this case though, a multi-channel analyzer was used that allowed for each channel to be distinguished. Finally, using the appropriate correction factors, one can convert the measured activity of the foil to neutron fluence.

The Superheated Drop or “Bubble Detector” is interesting because it consists of a small sealed vial containing several thousand microscopic sized droplets of a fluid held in two to three CC suspension of an inert fluid. For example, Freon can be held in a polymer or gel matrix (Knoll, 2000). During the manufacturing process, the pressure and temperature of the solution are controlled in such a way that the suspension becomes “super-heated,” but remains in its liquid state. Only a trigger from a large energy deposition will cause the droplets to expand and “flash” into a bubble. The fast neutrons from the linear accelerator can provide this energy by depositing sufficient energy to induce the creation of a bubble. As the bubble expands, it will cause other droplets in the vicinity to expand as well and create a bubble that is visual to the naked eye. The bubbles then are counted manually, or an optical reader can be used. An optical reader is recommended for counting since it is difficult to determine the correct number of monitor units needed to produce a sufficient number of bubbles that are countable, but also keep the number down in order to limit counting errors. Furthermore, if an acoustic sensor is placed on the detector, it can be used as an active system. Each time a bubble is formed, the sensor records the sound and it is counted as one count. In order to distinguish between noise from impact or vibration and an actual bubble, another sensor is placed in
the vicinity, independent of the vial to record background pulses. Both sets of data are compared and duplicate pulses indicate a “non-bubble” event and can be subtracted from the final total count.

After investigating these options for neutron detection, the moderated gold foil method was chosen. This decision was based on its ease of implementation and availability of materials.

The overall objective of this research is to measure neutron fluence generated from the Siemens Oncor Linear Accelerator in order to add to the existing data available in current literature for various linear accelerators. The specific objectives are as follows:

1. Determine the neutron source strength (Q) for the Oncor accelerator;
2. Determine the peripheral dose due to neutrons from the Oncor accelerator;
3. Determine the in-beam dose from neutrons from the Oncor accelerator; and
4. Determine the neutron head leakage from the Oncor accelerator.
LITERATURE

In 1959, Stevens and Smith (1959) of the Radiation Laboratory of the University of California at Berkley recognized that the increased understanding of the linear accelerator required additional information regarding the neutron flux that existed in the vicinity. Since most areas surrounding the accelerators are inaccessible, they required a method for surveying these locations remotely, but without the use of large amounts of electronic equipment. Their research showed that activation of indium foils by thermal neutrons could be applied to measurements of fast neutrons if the foils were placed in a paraffin sphere and covered by cadmium metal. This allowed the fast-neutrons to be slowed to thermal energies, and also allowed for filtering of the thermal room neutrons from the measurement, thus initiating the development of neutron measurements using an activated metal foil.

Twenty years later, after various measurements had been performed on several types of machines, Fox and McAllister (1977) noticed a difference in measured values by as much as a factor of 300 from a 25 MeV betatron and made measurements using neutron activation of aluminum foils. This method utilized neutron spectra obtained by interpolation between published values and neighboring elements. They found that the neutron fluence was not largely dependent on field size in the absence of a water phantom at the energy range of 18 to 23 MeV. With a phantom in place, the neutron fluence was found to increase up to 10%, depending on the field size. At 23 MeV, the dose to the patient was found to be $2.2 \times 10^{-6}$ neutron Gy per Gy of x-rays (0.002 mGy) within the treatment fields and $3 \times 10^{-7}$ at 20 cm outside the field (0.0003 mGy) with an uncertainty of 50%.
Soon after, in 1978, Gur, et. al. (1979) compared the neutron contamination of three different 18 MV photon beams in order to determine if the reported differences were due to machine characteristics or measurement flaws. Using aluminum foil activation, they found a neutron dose rate ratio of 6.7:3.7:1 for a Philips, Schimadzu, and Siemens accelerators, respectively. This supported the fact that machine design can cause significant differences in neutron production with various machines. They also reported an inherent measurement error of 20%.

With the increased number of linear accelerators being produced with the capability of operating with high-energy beams (>10MV), researchers were beginning to believe that these machines were not capable of maintaining the low level of leakage radiation from the machine head. So in 1981, McCall (1981) performed a series of measurements because he felt that much of the previously reported data was inaccurate and that neutron production was greatly misunderstood. At the conclusion of the research, he and his colleagues at the Stanford Linear Accelerator Center (Jenkins, Shore, and Swanson), had developed a simple and effective way to measure neutrons that has become to be called the “McCall Cookbook Method” (1981).

Around the same time the McCall Method was seeing its occurrence, McGinley and Kelly (1982) performed research to analyze the effect of the cadmium shield on in-beam neutron measurements. He looked at beams with endpoint energies ranging from 10 MeV to 45 MeV and found that the cadmium shield produced an apparent fluence of $8.93 \times 10^6$ n/cm$^2$ per photon Gy for a 33 MV x-ray beam. They also found that the cadmium induced fluence could be decreased about 70% if the beam only struck the top and bottom of the cadmium shield.
In 1986, the American Association of Physicists in Medicine produced report number 19 (TG-27) which summarized the findings of McCall and McGinley and others. The document was entitled “Neutron measurements around high energy x-ray radiotherapy machines” and in it, the most common and user-friendly procedures were outlined and presented in a concise format. Most importantly, report number 19 presented a procedure to follow when performing neutron measurements using gold foil activation on linear accelerators. It also listed some of the shortcomings and differences between using gold foil and indium foil.

Due to the lack of publications concerning in-beam neutron contamination, in 1988, McGinley performed measurements on several Varian 1800 and Siemens KD accelerators. Using moderated gold foils, he found the average neutron fluence from the Siemens machines to be $9.2 \times 10^6 \text{n/cm}^2/\text{photon Gy}$ for a 20 MV nominal beam and $1.27 \times 10^7 \text{n/cm}^2/\text{photon Gy}$ for the Varian 1800 18 MV nominal beam. Ten years later, McGinley produced a book dedicated to accelerator room shielding based on his and others past measurements. This book provides a wealth of information for room shielding including a section on neutron production, shielding, and dosimetry and lists the culmination of source strengths (Q) and dose equivalent’s of various accelerators.

Most recently, in 2002, Followill, et. al. (2003) from The University of Texas, M.D. Anderson Cancer Center, produced a paper consisting of measurement data for several linear accelerators. With this publication, they provide a current consolidated listing of source strength values for four popular accelerator manufactures, Varian, Siemens, Elekta, and GE. They found the average Q to be around $0.98 \times 10^{12} \text{n/Gy}$ with
a range of $0.2 \times 10^{12} \text{ n/Gy}$ to $2.4 \times 10^{12} \text{ n/Gy}$. The research done by Followill et. al. was the basis for this current research.
MATERIALS

1. Siemens Oncor Linear Accelerator.
2. Two polyethylene cylinders, 15.2 mm in diameter and 7.6 mm thick.
3. 0.025” cadmium metal sufficient to cover the polyethylene cylinders.
4. Two 99.9% Pure Gold Foils 2.54 mm in diameter and 0.025 mm thick.
5. Capintech Captus 3000 multi-channel analyzer (MCA).
METHODS

In order to accurately measure neutron fluence in an environment flooded with high-energy photons, the method requires that the system be insensitive to those same photons. The methods utilized in this research were derived from AAPM Report 19 (TG-27) and a recent publication by Followill et. al. (2003). The procedure satisfies the requirements of being insensitive to intense photon fields while maintaining a relatively high sensitivity to neutrons. The two gold foils were sent to the Radiological Physics Center (RPC) at M.D. Anderson in Texas for cross-calibration. This procedure requires the gold foils to be irradiated, and hence activated, by a neutron field and then measured on a NIST traceable calibrated counting system to determine the activity of the foil. This number then is compared to the reading obtained on a different (non-calibrated) counting system. After back-correction of the activity, these values are compared and a correction factor is obtained to convert the second system to the first. This resulting correction factor then is applied to the original calibration factor as supplied by the RPC. The end result is a counting system that is traceable to NIST.

The original calibration factor as supplied by M.D. Anderson was determined by sending several gold foils of known mass to the National Institute of Standards and Technology, where they were irradiated using the research reactor in a well known neutron fluence (±/− 2%). The foils then were read on the home counting system to determine the count rate to neutron fluence relationship. The calibration factor, as supplied by M.D. Anderson, was $3.515 \times 10^6$ (n cm$^{-2}$ per count s$^{-1}$) (Followill, et. al, 2003).
The source of neutrons used for calibration of the foils for this study was a Varian, 2100EX Linear Accelerator operating at 18MV. The foils were exposed to 12,000 monitor units at RPC and the activity was measured at two different intervals. The first was immediately following the irradiation and the second was approximately 12 h later. The foils then were shipped overnight to Blanchard Valley Regional Cancer Center (BVRCC) for measurement on our counting system.

The foils were measured on a Capintec Captus 3000 multi-channel analyzer and back corrected to the time of irradiation. The value obtained by M.D. Anderson was divided by the value obtained at BVHA to obtain the conversion factor for each foil. These values then were averaged in order to obtain the final activity to neutron fluence conversion factor (Table I) for the gold foils. Table I lists the values used for determining the correction factor for the Captus 3000 at Blanchard Valley Regional Cancer Center. The final calibration factor value used for this study was $6.91 \times 10^6$ (n cm$^{-2}$ per count s$^{-1}$).

Table I. Values Used for Determination of the Correction Factor for the Captus 3000

<table>
<thead>
<tr>
<th></th>
<th>Initial Activity (Followill, et. al.)</th>
<th>Measured Activity</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foil #1</td>
<td>4922.7</td>
<td>2472.9</td>
<td>1.991</td>
</tr>
<tr>
<td>Foil #2</td>
<td>4679.4</td>
<td>2409.2</td>
<td>1.942</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>Average</strong></td>
<td><strong>1.966</strong></td>
</tr>
</tbody>
</table>

The first step in performing the irradiations was to measure the starting or residual activity in the gold foils in the region of interest (Figure 6).
Figure 6. Background Spectrum Showing Approximately 20 Counts Per Minute Over the Region of Interest (channels 200 to 212) and the Background Contamination Peak from Cs-137 (origin unknown)

This was subtracted from the final activity to give the amount of activity induced in the gold foils due to the neutron fluence only. The gold foil then was placed between the two 3”x6” polyethylene moderators which were covered in 0.025” cadmium metal (Figures 7, 8, and 9) and placed at a distance of 140 cm from the target in the patient plane. The collimators were set at a 20x20cm field size for the Q value and peripheral dose measurements and the jaws were closed for measurement of the neutron leakage. For neutron leakage, the foils were placed at a distance of 104cm from the target, following the recommendations of TG-27. The foils were exposed to approximately 5000 to 9000 MU, depending on the measurement, in order to attempt to maintain a constant neutron induced activity, delivering approximately 50 to 90 Gy to D_{max} photon dose. The isocenter dose measurements were taken with the moderator placed in the beam and the foil at 100cm SAD with a 20x20cm collimator setting.
Figure 7. Siemens Oncor Linear Accelerator with Polyethylene Moderator 50cm Out from Gantry

Figure 8. Close Up of Neutron Moderator in Cadmium Shell with Gold Foil in Center
Figure 9. From Left to Right, Assembled Neutron Moderator, Polyethylene Moderator, and Cadmium Filter Assembly

A 20x20 collimator setting is used such that the entire moderator was within the radiation field. In order to convert the delivered MU to photon dose, an output factor of 1.07 was applied to the delivered dose. The accelerator was then run for approximately 10 to 15 min at the various locations (Figure 10) in order to deliver 25 to 35 monitor units to the foils. At the completion of the dose delivery, the foils were placed back in their protective case and stored until the time of measurement.
After a 12 to 24 h waiting period, the activated gold foils (Au-198) were read on a Capintec 3000 multi-channel analyzer with a window of 400 to 424 KeV and the peak at 412 KeV. Figure 11 shows an actual spectrum obtained from an irradiation. The activity is centered on channel 212. The measured activity (background subtracted) was back-corrected to the time of irradiation (Equation 1). The measured activity then was converted to neutron fluence (Equation 2) and the appropriate conversion factors were applied to determine the dose and source strength. For determination of the dose, a fluence to dose conversion factor of $6.83 \times 10^6$ (n/cm$^2$/mSv) was used for the peripheral dose measurements and $3.08 \times 10^6$ (n/cm$^2$/Gy) was used for the in-beam dose.
The peak at channel 206 is the 412 keV peak of radioactive Au-198.

Equation 1. Back-correction of activity:

\[ A_{bc} = A_0 \times e^{(0.693 \times t_d / T_{1/2})} \]

where \( A_{bc} \) is the back-corrected activity, \( A_0 \) is the initial activity, \( t_d \) is the wait time after irradiation, and \( T_{1/2} \) is the half life of Au-198.

Equation 2. Calculation of neutron fluence:

Neutron Fluence (n/cm\(^2\)/Gy) = \( A / g \times 6.91 \times 10^6 \times (n/cm^2/g/cps) / Gy \), where \( A \) is the final activity, \( g \) is the mass of the foil, and Gy is the dose to water delivered to the moderator.
Analysis performed by McCall, et. al. (1979, 1999) determined that the neutron fluence in a treatment could be described as the sum of the direct, scatter, and thermal components of the neutron spectrum which are summarized by the following equation:

\[ \Phi_{\text{dir}} = \frac{aQ}{4\pi d^2}, \Phi_{\text{sc}} = \frac{5.4aQ}{S}, \text{ and } \Phi_{\text{th}} = \frac{1.26Q}{S}, \]

where \( a \) is the transmission factor (\( a = 1 \) for lead), \( Q \) is the source strength, \( d \) is the distance from the source, and \( S \) is the surface area of the room. These can be rearranged to the following equation:

\[ Q = \Phi / \left( \frac{1}{4\pi d^2} + \frac{5.4}{S} + \frac{1.26}{S} \right). \]

Substituting the measured values into the equation results in the source strength (\( Q \)) in units of n/Gy \( \times 10^{12} \).

The calculation of dose was done following the method outlined in AAPM TG-27. The average neutron energy used was 1.97, which provided a dose conversion factor of 6.83\( \times 10^6 \) n/cm\(^2\)/mGy. This factor utilizes only the fast neutron fluence because the scatter and thermal component have been previously determined using Monte-carlo techniques. For the in-beam measurements, a modified version of the formula was used, which utilized only the direct neutron component due to the predominance of direct neutrons through the jaws. This conversion factor was 3.08\( \times 10^6 \) n/cm\(^2\)/mGy.
RESULTS

Tables II through VIII show the results of the neutron measurements. The average fast neutron fluence from the 20cm x 20cm field was $1.82 \times 10^6 \text{n/cm}^2/\text{Gy}$ and the average thermal neutron fluence was $0.45 \times 10^6 \text{n/cm}^2/\text{Gy}$. The combined measured fluence resulted in a $Q$ value of $0.33 \times 10^{12} \text{n/Gy}$ which compares well to the Siemens Primus $Q$ value of $0.20 \times 10^{12} \text{n/Gy}$ for a 15MV photon beam (Followill) and $0.35 \times 10^{12} \text{n/Gy}$ for an 18MV (energy corrected). The neutron fluence from the Oncor delivered a dose equivalent of 0.27 mSv/Gy at a 100cm radius from isocenter (no scattering medium present).

Table II. Raw Data Collected for Fast Neutron Fluence with 20x20cm Collimator Setting

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Count Rate (CPM)</th>
<th>% Error</th>
<th>Dose (Gy)</th>
<th>Fluence (n/cm$^2$/Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100cm Out</td>
<td>179 +/- 13.38</td>
<td>7.47%</td>
<td>54</td>
<td>1.53E+06</td>
</tr>
<tr>
<td>50cm In</td>
<td>299 +/- 17.29</td>
<td>5.78%</td>
<td>54</td>
<td>2.55E+06</td>
</tr>
<tr>
<td>100cm Out</td>
<td>340 +/- 18.44</td>
<td>5.42%</td>
<td>107</td>
<td>1.46E+06</td>
</tr>
<tr>
<td>50cm In</td>
<td>454 +/- 21.31</td>
<td>4.69%</td>
<td>83</td>
<td>2.51E+06</td>
</tr>
<tr>
<td>100cm (270 deg)</td>
<td>281 +/- 16.76</td>
<td>5.97%</td>
<td>96</td>
<td>1.34E+06</td>
</tr>
<tr>
<td>100cm (90 deg)</td>
<td>321 +/- 17.92</td>
<td>5.58%</td>
<td>96</td>
<td>1.54E+06</td>
</tr>
</tbody>
</table>

Average 1.82E+06

Table III. Raw Data Collected for Thermal Neutron Fluence with 20x20cm Collimator Setting

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Count Rate (CPM)</th>
<th>% Error</th>
<th>Dose (Gy)</th>
<th>Fluence (n/cm$^2$/Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100cm (270 deg)</td>
<td>70 +/- 8.37</td>
<td>11.95%</td>
<td>75</td>
<td>4.31E+05</td>
</tr>
<tr>
<td>100cm (90 deg)</td>
<td>73 +/- 8.54</td>
<td>11.70%</td>
<td>75</td>
<td>4.49E+05</td>
</tr>
</tbody>
</table>

Average 4.40E+05
The neutron fluence measured at the isocenter for a 20x20cm collimated field was $2.95 \times 10^6 \text{n/cm}^2/\text{Gy}$ which gives a dose at isocenter of 0.958 mGy/Gy with no scattering medium other than the neutron moderator.

Table IV. Raw Data Collected for In-beam Neutron Fluence with 20x20cm Collimator Setting

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Count Rate (CPM)</th>
<th>% Error</th>
<th>Dose (Gy)</th>
<th>Fluence (n/cm$^2$/Gy)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isocenter</td>
<td>585 +/- 24.19</td>
<td>4.13%</td>
<td>37</td>
<td>2.88E+06</td>
</tr>
<tr>
<td>Isocenter</td>
<td>426 +/- 20.64</td>
<td>4.85%</td>
<td>27</td>
<td>3.03E+06</td>
</tr>
</tbody>
</table>

* Corrected for Cd contamination

The fast neutron leakage through the accelerator head was $2.8 \times 10^6 \text{n/cm}^2/\text{Gy}$. This figure was measured at 28cm out from the isocenter in the patient plane as recommended by AAPM report No. 19, page 9.

Table V. Raw Data Collected for Fast Neutron Fluence with Collimators Closed

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Count Rate (CPM)</th>
<th>% Error</th>
<th>Dose (Gy)</th>
<th>Fluence (n/cm$^2$/Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28cm Out</td>
<td>478 +/- 21.86</td>
<td>4.57%</td>
<td>75</td>
<td>2.94E+06</td>
</tr>
<tr>
<td>28cm In</td>
<td>349 +/- 18.68</td>
<td>5.35%</td>
<td>64</td>
<td>2.51E+06</td>
</tr>
<tr>
<td>28cm (270 deg)</td>
<td>336 +/- 18.33</td>
<td>5.46%</td>
<td>54</td>
<td>2.89E+06</td>
</tr>
<tr>
<td>28cm (90 deg)</td>
<td>331 +/- 18.19</td>
<td>5.50%</td>
<td>54</td>
<td>2.85E+06</td>
</tr>
</tbody>
</table>

Average 2.80E+06
### Table VI. Neutron Source Strengths for Various Linear Accelerators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Energy</th>
<th>Q (n/Gy) (x10^{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian</td>
<td>1800</td>
<td>18</td>
<td>0.92</td>
</tr>
<tr>
<td>Varian</td>
<td>1800</td>
<td>15</td>
<td>1.22</td>
</tr>
<tr>
<td>Varian</td>
<td>1800</td>
<td>10</td>
<td>0.76</td>
</tr>
<tr>
<td>Varian</td>
<td>2100C</td>
<td>18</td>
<td>0.96</td>
</tr>
<tr>
<td>Philips</td>
<td>SL-25</td>
<td>22</td>
<td>2.37</td>
</tr>
<tr>
<td>Philips</td>
<td>SL-20</td>
<td>17</td>
<td>0.69</td>
</tr>
<tr>
<td>Electa</td>
<td>SL-20</td>
<td>17</td>
<td>0.69</td>
</tr>
<tr>
<td>Electa</td>
<td>SL-25</td>
<td>18</td>
<td>0.46</td>
</tr>
<tr>
<td>Electa</td>
<td>SL-25</td>
<td>18</td>
<td>0.46</td>
</tr>
<tr>
<td>Electa</td>
<td>22</td>
<td>2.37</td>
<td></td>
</tr>
<tr>
<td>Electa</td>
<td>SL-25</td>
<td>25</td>
<td>1.44</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 41</td>
<td>12</td>
<td>0.24</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 41</td>
<td>15</td>
<td>0.47</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 43</td>
<td>18</td>
<td>1.50</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 43</td>
<td>25</td>
<td>2.40</td>
</tr>
<tr>
<td>Siemens</td>
<td>MD</td>
<td>15</td>
<td>0.20</td>
</tr>
<tr>
<td>Siemens</td>
<td>KD</td>
<td>18</td>
<td>0.88</td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus</td>
<td>15</td>
<td>0.20</td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus</td>
<td>18</td>
<td>0.35 Calculated</td>
</tr>
<tr>
<td>Siemens</td>
<td>Oncor</td>
<td>18</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* McGinley  
** Folowill, et. Al.  
*** This research

### Table VII. Neutron Dose Equivalent (H_0) in Patient Plane of Various Linear Accelerators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Energy</th>
<th>H_0 (mSv per Photon Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian</td>
<td>1800</td>
<td>18</td>
<td>1.02 - 1.60</td>
</tr>
<tr>
<td>Varian</td>
<td>1800</td>
<td>15</td>
<td>0.79 - 1.30</td>
</tr>
<tr>
<td>Varian</td>
<td>1800</td>
<td>10</td>
<td>0.04</td>
</tr>
<tr>
<td>Philips</td>
<td>SL-25</td>
<td>25</td>
<td>2.00</td>
</tr>
<tr>
<td>Philips</td>
<td>SL-20</td>
<td>20</td>
<td>0.44</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 41</td>
<td>12</td>
<td>0.09</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 41</td>
<td>15</td>
<td>0.32</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 43</td>
<td>18</td>
<td>0.55</td>
</tr>
<tr>
<td>GE</td>
<td>Saturn 43</td>
<td>25</td>
<td>1.38</td>
</tr>
<tr>
<td>Siemens</td>
<td>KD</td>
<td>20</td>
<td>1.10 - 1.24</td>
</tr>
<tr>
<td>Siemens</td>
<td>MD</td>
<td>15</td>
<td>0.17</td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus</td>
<td>15</td>
<td>0.18 *** Calculated</td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus</td>
<td>18</td>
<td>0.32</td>
</tr>
<tr>
<td>Siemens</td>
<td>Oncor</td>
<td>18</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* McGinley  
** This research  
*** Calculated using published Q values
Table VIII. In-beam Dose Due to Neutron Contamination of Various Linear Accelerators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Energy</th>
<th>Neutron Dose (mGy per Photon Gy)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian*</td>
<td>1800</td>
<td>18</td>
<td>0.530</td>
</tr>
<tr>
<td>Varian*</td>
<td>1800</td>
<td>15</td>
<td>0.270</td>
</tr>
<tr>
<td>Varian*</td>
<td>1800</td>
<td>10</td>
<td>0.007</td>
</tr>
<tr>
<td>Siemens</td>
<td>Oncor</td>
<td>18</td>
<td>0.958</td>
</tr>
</tbody>
</table>

* Corrected for Cd contamination and room scattered neutrons
* P. H. McGinley and J. C. Landry, 1988
DISCUSSION

The results indicate that the measured neutron fluence and calculated Q value from the Siemens Oncor are slightly higher than published values for the 15 MV Siemens Primus accelerator, but compares well to the Primus when the energy is corrected to an 18 MV beam. Taking into account the local error of measurements and the inherent 20% margin of error for neutron measurements (Gur, 1979), it is within the published values for other accelerators including the Siemens KD (Figure 12). The observed difference between the Oncor and Primus accelerators is difficult to determine. Speculation can take into account the various room sizes, which will affect the scatter and thermal component or possibly foil location, moderator size, Cd covering, relative number of high energy photons in the beam, or general head design. Looking at each of these factors, one can conclude that the number of high-energy x-rays in the beam could greatly affect the neutron production. This is due to the peak at which photo-neutron production is greatest, around 13 MeV since, on either side of this peak, the cross-section drops off abruptly and will cause a decrease in the number of neutrons produced.

The peripheral dose due to neutrons also falls within other published data (McGinley, 1998) and is within the guidelines of less than 0.1% dose from contamination and head leakage. The dose at isocenter was not compared to any other machines due to the lack of data in literature; however, the dose seems reasonable given the lack of collimator shielding in the direct photon beam. The lack of shielding in this area allows the direct fast neutrons to become a major part of the dose during high-energy treatments.
Figure 12. Plot of Neutron Source Strength (Q) Versus Manufacturer for 18MV Photons (error bars are +/- 20%)

*The Siemens Primus accelerator operates at 15 MV. The data represented were adjusted to 18 MV for comparison to the Oncor. Taking the relative number of photons in the high-energy region of the spectrum and comparing it to the effective cross section at this energy provided the means to determine the correction factor.

An interesting outcome of this research was the ability to visualize the different energy peaks during the readout using the multi-channel analyzer. For the peripheral dose measurements, it was very easy to determine the peak of interest. But for the in-beam measurement, multiple peaks were observed, although only one additional was expected. Figure 13 is the spectrum obtained from one of the in-beam measurements. It shows that the foil irradiated in beam had the expected peak of 412 keV, but also had a
peak at around 350 keV. A much larger peak (around twice the activity) at 75 keV also was observed.

Figure 13. Measured Spectrum of Gold Foil Irradiated at 100cm SAD, in Beam with 20x20 Collimator Setting

The peak at channel 206 is the 412 keV photon from the decay of Au-198. The smaller peak at channel 175 is the 344 keV peak from the decay of Au-196 to Pt-196 and the peak at around channel 340 is the same peak that is seen the other spectra from Cs-137.

The first reaction that takes place in both the in-beam and peripheral exposures is the creation of Au-198 via a \((n, \gamma)\) reaction with Au-197. This is the reaction that is responsible for the 412 keV peak in the spectrum used for calculating neutron fluence:

\[
(n, \gamma) \quad \text{Au-197} \rightarrow \text{Au-198}
\]

This reaction creates the Au-198 isotope having a 2.7d half-life and decays to Hg-198 with the emission of the 412 keV photon:

\[
\text{Au-198} \rightarrow \text{Hg-198} + \gamma (412 \text{ keV})
\]
A second reaction, which takes place due to the direct radiation incident on the Au-197, is the creation of Au-196. This isotope has a half-life of 6d and decays to stable Pt-196 with an average energy emission of 344 keV:

\[
\text{Au-196} \rightarrow \text{Pt-196} + \gamma (344 \text{ keV}), 92.5\% \\
\text{and:} \\
\text{Au-196} \rightarrow \text{Hg-196} + \gamma (426 \text{ keV}), 7.5\%.
\]

The spectrum in Figure 13 also shows the characteristic peaks from NaI detectors. The small “hill” at approximately 660 keV (channel 330) is the sum peak of the 344 and 412 keV photons. The large peak at 70 keV is the k-shell x-ray from lead shielding of the NaI detector. It is interesting to note that the characteristics of the spectrum is very similar to those of other isotopes such as Co-60 and Cs-137, by displaying sum peaks, backscatter and bremsstrahlung, and k-shell peaks.

Had this measurement been performed with a GM counter, two significant problems would have arisen. First, all peaks would have been included in the total activity measurement which would have lead to a higher measured activity. Second, the different half-lives of the contamination isotopes would have lead to an error with the back-correction. The combined errors would have lead to the neutron contamination being misinterpreted and, most likely, greatly overestimated.

Much is known about the biological effects of radiation. Energetic neutrons in the treatment room generally have a weighting factor of 10 to 20. Although not applied to the dose equations, these weighting factors affect the relative biological effect (RBE) of any particular radiation and causes to increase the damage done due to the particular radiation. This knowledge provides a good foundation in evaluating the risk factor when
using high-energy photons with IMRT. If one considers a conventional 3D conformal plan of 70 Gy for the treatment of prostate cancer, the monitor units (MU) per fraction would be around 320. At 180 cGy/day, the total MU’s becomes 12600, over the course of treatment. For the purpose of this comparison we can assume that the effective neutron dose is proportional to the number of monitor units and that one Gy = 100 MU. Given the calculated peripheral dose of 0.27 mSv per Gy (100MU) we get the following whole body equivalent doses:

$$0.27 \text{ mSv/100MU} \times 12600\text{MU} = 34 \text{ mSv}.$$  

Since a standard IMRT plan can deliver two to three times the number of monitor units for a given dose, an IMRT plan has the potential of delivering 68 to 102 mSv over the course of treatment.

If 20 mSv is used for a standard whole body CT scan, one finds that the peripheral neutron dose is about two times greater than that from a whole body screening CT scan and an IMRT plan delivers about six times. The ICRP has determined that the risk associated with a whole body exposure of low dose rate radiation is 4% per Sv (Hall, 2000). Given this, the risk from a 70 Gy IMRT treatment is approximately 0.5% of having detrimental effects. Further more, the U.S. Food and Drug Administration has stated that a 10 mSv CT examination can be attributed to a 1 in 2000 chance of developing a fatal cancer. The dose calculated from the IMRT treatment then would correspond to 1 in 75. However, given the fact that those receiving this much neutron dose would already be under treatment for cancer and that the natural incidence of fatal cancers of about 1 in 5, the risk from peripheral neutron dose appears to be minimal.
It has been shown that the neutron dose is much more significant at peripheral locations due to the predominant nature of photon dose near the isocenter. Given the difficulty in delivering homogeneous doses to very large and/or deep tumors, the choice to use high-energy photons in IMRT seems reasonable. However, it is recommended that individuals performing or planning to perform 18MV IMRT take these studies into account.

No difficulties were experienced with the performance of this research. The procedures described in the literature provided sufficient information for the set-up and exposure of the gold foils for activation. Two considerable downfalls were observed, however. The first is the cost of materials. It has been have suggested that this type of measurement is capable of being readily performed in a clinical setting due to the availability of materials and their low cost. However, the cost for one moderator and two gold foils was approximately $800, with the majority of the cost going towards the gold foils. Also, since only two gold foils were purchased, one can acquire data for two locations only during one setting. Depending on the activity of the foil, one must wait at least 1 wk before irradiating the foils once again. This leads to a 1 mo period in order to acquire an appropriately large data set for analysis. Ideally, one should have four foils available for use, which would significantly reduce the research time needed.
CONCLUSION

The objectives of this research were acceptably met. The specific objectives were met are as follows:

1. The neutron source strength (Q) for the Oncor accelerator was found to be $0.33 \times 10^{12}$ n/Gy. This compared well to the Siemens Primus Q value of $0.20 \times 10^{12}$ n/Gy for a 15MV photon beam.

2. The peripheral dose due to neutrons from the Oncor accelerator was found to be $0.27$ mSv/Gy or about $0.03\%$ of the photon dose at a 100cm radius from the isocenter.

3. The in-beam dose resulting from neutron contamination was found to be $0.958$ mGy/Gy or almost $0.1\%$ of the photon dose. This value is reasonable based on current literature, yet minimal values currently exist for a proper comparison.

4. The neutron head leakage from the Oncor accelerator was found to be $2.8 \times 10^6$ n/cm$^2$/Gy, but was not compared to other accelerators due to the lack of data for modern head leakage.
SUMMARY

The work presented in this thesis documents the research conducted from April 2005 to November 2005. It describes the steps taken to measure and characterize the neutron fluence produced by the Siemens Oncor linear accelerator. The work delivers new information that should be useful in radiation therapy room shielding calculations and in treatment planning for patients undergoing radiation therapy. The importance of this is directly applicable to the field of Radiation Oncology, as neutron producing, high-energy photons become more prevalent in Intensity Modulated Radiation Therapy (IMRT).
REFERENCES


ABSTRACT

Moderated gold foil activation was used to measure the neutron fluence from the Siemens Oncor linear accelerator. Measurements were made both in the photon beam and in peripheral locations using 20x20cm jaw settings. The head leakage was measured as well, with the jaws closed as is prescribed in AAPM report 19. The neutron fluence values then were used to calculate source strength (Q) along with the respective equivalent doses. The neutron fluence from the 20cm x 20cm field resulted in a Q value of $0.33 \times 10^{12} \text{n/Gy}$. The peripheral dose equivalent was found to be 0.27 mSv/Gy at a 100cm radius from isocenter. The in-beam neutrons delivered a dose of 0.958 mGy/Gy. The total neutron leakage through the head was $2.8 \times 10^6 \text{n/cm}^2/\text{Gy}$, measured at 28cm out from the isocenter. It was found that the neutron production did not pose any risk greater than other machines currently available.