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Predicting electron insert output factors at nominal and extended source to surface distance

Ahmet Bulut

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PREDICTING ELECTRON INSERT OUTPUT FACTORS
AT NOMINAL AND EXTENDED SOURCE TO SURFACE DISTANCE

A Thesis
Submitted to Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
Requirements for the degree of
Master of Science

in
The Department of Physics and Astronomy

by
Ahmet Bulut
B.S., King Fahd University of Petroleum and Minerals, 1997
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ABSTRACT

Two Varian linear accelerators were used to test the modified sector-integration method. This method can predict the electron insert factor for arbitrary inserts at different source to surface distances (SSD). The effective source distances ($SSD_{eff}$) and insert factors (IF) for several accelerators are compared. The relationship of IF and $SSD_{eff}$ for machine type, energy, cone size, insert size and SSD is presented. The results were fed into the electron output determination module of an existing monitor unit calculator (MUCalc) which uses the modified sector integration method. Prediction and measurements were compared for various clinical inserts at several SSDs.
CHAPTER 1

INTRODUCTION

Cone inserts of various sizes and shapes are frequently used in electron radiation therapy. When the insert factor, defined as the ratio of the dose rate with and without the insert present, for such an insert is measured it may reach as low as 0.80. It is well documented that such inserts will change the radiation output; therefore physicists should account for this effect in order to determine the correct dose to be delivered. Individual patients may require unique inserts, and it is time consuming to perform this process for every insert. Hence, in the 1980’s, various empirical methods were examined to predict the effect of inserts on output and study this phenomenon. The goal of this thesis was to test a more general method of predicting the output of an electron beam for all clinical conditions; i.e., different energies, insert sizes and shapes, cone sizes and source to surface distances (SSD).

A. Background

After x-rays were discovered in 1895, there was a trend to use this new energy source to control, and cure when possible the spread some types of cancer. Radiation has primarily been used in two forms: photons and electrons. With the exception of radioisotopes irradiation, photons are created by accelerating electrons to hit a high Z target, like tungsten. In order to create high energy photons high energy electrons must be used.

The production of high energy electron beams has undergone many improvements. The Van De Graff electron accelerator was one of the earliest units to produce high energy x-rays (10 MV) using electrostaticly accelerated electrons. The
betatron, microtron and linear accelerator were later developed to produce high electron energies. Linear electron accelerators gained much popularity for several reasons, such as larger fields sizes, higher dose rates and higher energies. Rather than use photons to irradiate a tumor, electrons may be used directly without passing them through a target. This is particularly appropriate for tumors near the surface of the patient’s skin.

Modern linear accelerators have the ability to produce electron beam with energies in the range from 4 to 25 MeV. Whereas low energy electron beams are used to treat superficial cancers, the high energy beams are used for semi-deep-seated tumors. Electron radiation therapy, using linear accelerators, has an advantage over the low energy photons irradiation in many clinical applications, due to the sharp fall-off of electron dose deposition in the medium. Tapley points out that there is no alternative method to electron beam therapy for some types of treatment, no matter how complicated the photon beam is constructed. For example, electrons are superior to photons in irradiating surgical areas to prevent infestation. Moreover, electron beam may often be the best solution to boost treatment without irradiating deep structures i.e. lungs after mastectomy. Total skin electron therapy and intra-operative radiation therapy are other applications of high electron irradiation.

The International Commission on Radiological Units and Measurements (ICRU) recommends that dose delivered to a tumor to be within 5.0% of the prescribed dose. For this reason, when an insert is used in electron therapy treatment, an insert factor should be taken into account. This factor is defined as the ratio of radiation output of the cone with the insert divided by output of the cone without the insert (open cone). Typical values for this factor range from as low as 0.80 to as high as 1.03, where unity
ratio implies no effect on radiation output. It is clear that, in order to stay within the 5.0% criterion, the insert factor needs to be considered.

B. Electron Interaction

Since electrons have negative charges, they behave as charged interaction as they move through a medium. There are three main types of interactions: (1) by collision with an atom as whole, (2) by collision with an electron, (3) by radiative processes (bremsstrahlung) (Figure (1)). Excitation or ionization for the atom occurs when the electron interacts with it in a Coulombic manner. Bremsstrahlung, also due to Coulombic interaction, involves x-ray production and its probability is proportional to $Z^2$ (atomic number) and the incident electron energy. In water, electrons have an energy loss rate approximately equal to 2 MeV/cm. As a result, electron dosimetry is more difficult than photon dosimetry since the energy of the beam changes in very small distances within the medium. 

![Figure 1. Some electron interaction processes: a) excitation, b) ionization, c) bremsstrahlung production, d) characteristic radiation production. [Taken from reference (4)](image)
C. Linacs and Electron Production

Linear accelerators or “linacs” are machines that produce high electron beams by using high-frequency electromagnetic waves to accelerate charged particles in linear structures \(^1\). The general design of most modern linacs is shown in figure (2) \(^4\). There are five main structures: modulator, stand, gantry, console and treatment couch. Figure (2) does not show the console and the modulator. Sometimes, the modulator could be found in the stand (e.g. Varian 600C, Varian Associates, Palo Alto, CA). The couch is not a part of the radiation delivery system, however it is a main factor in the gantry installation and the patient setup. The console could be noted as the “brain” of the accelerator. It has the controlling circuit boards and tuning capacitors, used for output and steering adjustment. Daily operation is controlled from the console. The modulator is the power source of the accelerator. It transforms the alternating current (AC) to direct current (DC) which is needed by the components in the stand.

![Figure 2. A schematic view of the treatment unit emphasizing the geometric relationship of the linac and treatment couch motions.](image)

The stand contains the klystron which plays a primary role in amplifying the radiofrequency waves for accelerating the electrons. Water is used for cooling the pipes
and the target and connections are found in the stand. Also, the stand contains the sulfur hexafluoride (SF$_6$) gas used as a dielectric in the waveguide, which delivers microwave power from the klystron or magnetron to the accelerating structure. Klystrons and magnetrons serve similar functions as microwave amplifiers.

Figure (3) shows a cross-sectional diagram of a magnetron device. In the magnetron, electrons are generated from a cathode by thermionic emission, and they are attracted to the anode by a DC electric field. A perpendicular (to the cross-section) magnetic field applied in the anode cavities forces the electrons to make complex spirals, which leads to the production of the microwaves from the radiating energy of the electrons (figure (3)). A mechanical pump is used to produce a vacuum along the path from waveguide window to the treatment head window (figure (4)). This vacuum minimizes scattering and absorption of electrons. The resultant RF waves are guided by the waveguide to the accelerating structure in the gantry (figure (4)).

The treatment head located in the gantry contains many structures (figure (5)). The bending magnet changes the direction of the electron beam so it becomes perpendicular to the straight line from the accelerating structure. There are two main

Figure 3. A magnetron cross section. (a) and (b) a cavity magnetron; (c) space charge distribution and electron paths in a magnetron when oscillating. [Taken from reference (4)]
Figure 4. The major accelerator subsystems (Clinac 20). [Taken from reference (4)]

Figure 5. The Modern Varian Accelerator head internal structures. 2) Asymmetric Jaws Four independent collimators. 3) Ion Chamber Dual sealed ion chambers with 8 sectors. 4) 10-Port Carousel electron scattering foils. 5) Achromatic 3-Field Bending Magnet. 6) Real-Time Beam Control Steering System. 7) Circular Focal Spot Size less than 2 mm. 9) Gridded Electron Gun. [Taken from reference (5)]

types of bending magnets: 90° and 270°. The two machines used in this project have a 270° configuration. Electron beam is not affected by the primary collimator which is designed to confine the photon beam to a 30° cone (figure (6)). The scattering foils are used to scatter and spread the electron beam and they are made of steel or lead or both. The secondary collimator is a square aperture that confines the size of the beam at isocenter to a maximum of 40×40 cm² (figure (6)) supra. 5.
Ion chambers are located in the beam path in order to monitor the radiation output and dose rate (figure (7)) \cite{5}. Then the beam enters the two pairs of motor driven collimator jaws. These are “jaws” because they move in and out independently from each other in order to form different sizes of rectangular (or square) shaped field (geometrical field size) and they are made of tungsten. ICRU defines the geometrical field size as “the projection, on a plane perpendicular to the beam axis, of the distal end of the collimator as seen from the front center of the source” \cite{6}. In most clinical configurations, the upper two jaws are called Y-jaws and the two lower jaws are called X-jaws.
There is a vital relationship between the gantry, the gantry head and the treatment couch; i.e., their rotation axes meet at the isocenter (figures (2) and (6)). In modern machines the distance from the target to the isocenter typically equals 100.0 cm, and it is called the source axis distance (SAD) (figure (6)) \(^5\). But the electron are not produced from the target so the scattering foils may be considered as a source which is located at 87.5 cm from the isocenter (figure (6)) \(^5\).

D. Radiation Output

The report of American Association of physicists in Medicine (AAPM) Radiation Therapy committee task group No.51 has published a protocol for calibrating linacs, which was followed in calibrating the machines used in this project \(^7\). The machines are adjusted to deliver 1.00 cGy/MU at the depth of maximum dose, \(d_{\text{max}}\), using an SSD of 100.0 cm and a field size of 10×10 cm\(^2\) at the surface of the water phantom. Whereas cGy (rad) is the unit used for the dose delivered, MU denotes monitor units. A MU is a measure of the response of the ion chamber located in the head of the accelerator. The amount of the radiation delivered to a patient is stated in
MU. SSD, source to surface distance, is the distance from the target (photon source) to the surface of the patient or phantom (TSD). It should be noted that the definition of TSD is not altered from photon calibration, to electron calibration even though the target is not used in electron irradiation.

E. Electron Collimation and Effect on the Output

   Electron beam field sizes are determined (collimated) by applicators called “cones” and cutouts (figures (8) and (9)). Cutouts are interchangeably called inserts, and they act as a final field-defining aperture. Varian machine cones (used in this project) define a constant square field size that is different from the secondary collimators (jaws) (figure (9)). However, the jaw setting affects the electron beam characteristics and the opening is pre-set according to the energy and cone size selected and listed in table (1). Both machines used in the project have the same settings. As a result, when the electron therapy mode is chosen and the requested cone is inserted, the jaws move to the settings shown in the table. The collimator field size changes with
energy and cone size in order to get the optimum and the best profile. When the 6 MeV mode is chosen, for example, the jaws are opened to 20.0 cm $\times$ 20.0 cm if the 6 cm $\times$ 6 cm cone is inserted. The cone defines the field to be 6.0 $\times$ 6.0 cm$^2$ at isocenter.

Table 1. The collimator jaws opening (cm$^2$) for given cone sizes.

<table>
<thead>
<tr>
<th>Cone Size</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>6$\times$6 cm$^2$</td>
<td>20.0$\times$20.0</td>
<td>20.0$\times$20.0</td>
<td>11.0$\times$11.0</td>
<td>11.0$\times$11.0</td>
<td>11.0$\times$11.0</td>
</tr>
<tr>
<td>10$\times$10 cm$^2$</td>
<td>20.0$\times$20.0</td>
<td>20.0$\times$20.0</td>
<td>14.0$\times$14.0</td>
<td>14.0$\times$14.0</td>
<td>14.0$\times$14.0</td>
</tr>
<tr>
<td>15$\times$15 cm$^2$</td>
<td>20.0$\times$20.0</td>
<td>20.0$\times$20.0</td>
<td>17.0$\times$17.0</td>
<td>17.0$\times$17.0</td>
<td>17.0$\times$17.0</td>
</tr>
<tr>
<td>20$\times$20 cm$^2$</td>
<td>25.0$\times$25.0</td>
<td>25.0$\times$25.0</td>
<td>25.0$\times$25.0</td>
<td>23.0$\times$23.0</td>
<td>22.0$\times$22.0</td>
</tr>
<tr>
<td>25$\times$25 cm$^2$</td>
<td>30.0$\times$30.0</td>
<td>30.0$\times$30.0</td>
<td>30.0$\times$30.0</td>
<td>28.0$\times$28.0</td>
<td>27.0$\times$27.0</td>
</tr>
</tbody>
</table>

The cones used in this project are type III. As shown in figures (9) and (10), they consist of three hollow metallic squares with four legs connecting them in an open-wall configuration. The middle one is smaller than the others and the one closest to the patients is used to hold the insert. The black plastic pad shown is a safety interlock. If the cone hits something while the machine is moving, it stops.

Figure 10. The three hollow metallic squares for type III Varian cones

Besides defining the field, cones create a well defined beam profile in terms of symmetry and flatness. Another advantage of the design, four supports as opposed to walls is getting the lowest possible level of beam contamination from bremsstrahlung produced in the cone walls.$^8$
Three things must be specified in electron irradiation: energy, cone size and SSD. During the linac commissioning, data are collected for each cone with all available energies and at various clinical treatment distances. Unfortunately, not all patients could be treated with square fields. Three main techniques are used: skin collimation (mask), cone inserts (cutouts), and trimmers. Trimmers are rarely used anymore. Lipowitz metal and lead are used to make the masks and the inserts. Lipowitz metal is a fusible alloy consisting of 50% Bi, 26.5% Pb, 13.3% Sn and 10.2% Cd. The density is 9.39 g/cm$^3$ and the melting point of 158.0 °F. The advantages of Lipowitz’ metal include a low melting point, high density and that it is relatively non-toxic. This alloy has other commercial names such as cerrobend, alloy 158 and Ostalloy. Masks are placed on the patient’s skin directly so only the open cone output correction is necessary. However, two main things should be considered during cerrobend mask molding: correct shielding thickness and the edge effect of electron scattering.

During the machine commissioning, the characteristics of the electron beams are measured. The depth dose curve and related variables can be seen in figure (11). Depth dose refers to the ratio of the dose at a certain depth to the reference depth. The depth dose curve is usually constructed along the central axis of the beam and the reference depth for electrons is considered the $d_{\text{max}}$. We will discuss the following parameters: $E_0$, $R_{50}$, $R_p$ and $d_{\text{max}}$ (in figure (11), $z_m$ refers to $d_{\text{max}}$). $E_0$ is the mean electron beam energy. $R_{50}$ is the depth where the 50% of the ionization dose is delivered. $R_p$ is the practical range of the electrons. $d_{\text{max}}$ is the depth where the maximum dose or 100% delivery occurs. Two more characteristics are determined for each cone: the cone ratio and the effective source distance ($SSD_{\text{efl}}$). The cone ratio is defined as the quotient of
the open cone output to the output of the reference field (usually open 10×10 cm² cone) at the reference SSD (usually 100.0 cm) and d_{max}.

The inverse square law (ISL) is used to correct the radiation output for geometrical losses, i.e., the radiation intensity falls off as the inverse of the square of the distance from the source of the radiation. In electron beam dosimetry, it is found that the simple inverse square law using the nominal SSD does not give an accurate output correction. As discussed above, electron beam faces multiple interactions and scatterings after exiting the vacuum window of the accelerating structure. For this reason, unlike photon beams coming from the linac target, electron beams appear to emanate from a point down the stream from the treatment head. That point could be the scattering foils as discussed earlier. As a result, the ISL \[ \frac{I_{SAD}}{I_{SSD}} = \left( \frac{SAD}{SSD} \right)^2 \] can not be applied using the distance from the target to the treatment surface or TSD.

Two approaches have been introduced to solve this problem. The effective source to surface distance (SSD_{eff}) and the virtual source surface distance (SSD_{vir}) can
be used to calculate the ISL factor. The SSD_{eff} and SSD_{vir} are very close in value, but the SSD_{eff} has the advantage of including the effect of the air gap discussed below. In this project, the SSD_{eff} was used. Khan proposed a method of measuring this value, as shown in equation (1), which represents the corrected ISL using SSD_{eff}. \( I_o \) and \( I_g \) are the outputs at SAD and at SSD respectively \(^1\). The air gap (g) is the distance difference between the SAD and the treatment SSD as shown in figure (12). It can be negative as in the case of SSD=99.0 cm (99.0 - 100.0 = -1.0 cm). Equation (1) may be rewritten as a first degree polynomial (i.e., \( y = ax + b \), \( a \) = slope), SSD_{eff} is defined in terms of the gap and \( d_{\text{max}} \) using the slope of the line as shown in equation (2).

\[
\frac{I_o}{I_g} = \frac{I_{SAD}}{I_{SSD}} = \left( \frac{SSD_{eff} + d_{\text{max}} + g}{SSD_{eff} + d_{\text{max}}} \right)^2 \\
\Rightarrow \frac{I_{SAD}}{I_{SSD}} = \frac{g}{SSD_{eff} + d_{\text{max}}} + 1
\]

\( \text{slope} = \frac{g}{SSD_{eff} + d_{\text{max}}} ; SSD_{eff} = \frac{g}{\text{slope}} - d_{\text{max}} \)  

\[ (2) \]

---

**Figure 12.** The air gap and how it is measured
CHAPTER 2
LITERATURE SURVEY

A main goal of this thesis research was to be able to predict the output correction for regular and/or irregular shaped cutouts using mathematical equations fitted to measured results, using the least number of measurements possible. Several authors have tried to explain and model the phenomena involved. This survey is in chronological order. There are seven methods used to predict electron output factors.

1. **Equivalent square method** In (1997), Biggs, et al., wrote one of the first papers about predicting the electron beam output from irregularly shaped fields. They did not use the insert factor terminology, but used cone ratios instead. Equation (3) was used to calculate the dose using the cone ratio.

\[
Dose = M \times \text{calibration factor} \times \text{cone ratio} \times PDD
\]  

Where M is the number of monitor units, PDD (percent depth dose) is the ratio of the dose delivered at depth \(d\) to the dose delivered at \(d_{\text{max}}\). The cone ratio is defined as the ratio of the dose at \(d_{\text{max}}\) for a field size to the dose at \(d_{\text{max}}\) for the reference field. All these parameters are electron-energy dependent. Equivalent square versus cone ratio charts were created for cones and energies used. The author proved that movable jaws cause changes in dose delivered. For rectangular fields, they showed that cone ratios follow the same trends as square and circular inserts except for high aspect ratio cases. The aspect ratio is defined as the ratio between the length and width of a rectangle (i.e. unity for squares). Thus, this method works very well under the two conditions; constant SSD and large field sizes. Kubo (1990) made measurements using a new cone...
generation\textsuperscript{10}. He compared his results with the results of Biggs (1997) and found that the differences in outputs for low energies and small cones are mainly due to photon jaw settings. However, McParland \textit{et al} (1992) concluded in a subsequent analysis that using equivalent fields could give inaccurate results because of the lateral scattering disequilibria; that is, central axis dosimetry depends on the scattering from the field edges\textsuperscript{11}.

2. \textbf{Square root method (SQM)} Mills \textit{et al} used the theory of multiple Coulomb scattering (Fermi-Eyges theory) to predict the distribution of an electron pencil beam\textsuperscript{12}. Equation (4) was generated where \( OF \) is the output factor and \( wx \) and \( wy \) represent sides of the field and. They found that the resulting equations did not agree with measurements. The reason, mentioned in the paper, was neglecting the effect of collimator scattering.

\[
OF^{wx,wy} = \sqrt{OF^{wx,wx} \cdot OF^{wy,wy}}
\]  

(4)

3. \textbf{Pencil beam method} Bruinvis \textit{et al.} employed a two-dimensional Gaussian pencil beam model for calculation of the dose distribution at various depths. They derived formulas for: accelerator beams with no applicators, treatment beams with applicators and the frame scatter dose. For the photon dose component, they used a single exponential expression. The formalism in equation (5) for the dose distribution

\[
D(z, x, y) = P(z)\phi(z, x, y)
\]  

(5)

was used, where \( P(z) \) is the depth dose and \( \phi \) term has machine dependent variables (\( r_w \) and \( \sigma_z \)) to be measured. Also, this paper gave a detailed explanation of side scattering from field edges and found that it could be represented by these two measured variables.\textsuperscript{13}
\[
\phi_R(z,0,0) = \frac{n}{\pi (r_w^2 + 2\sigma_z^2)} \left[ 1 - e^{-\frac{-r_w^2 + 2\sigma_z^2}{2\sigma_z^2}} \right]
\]

4. **One-dimensional method** Mills *et al* (1985) added another term to the one-dimensional method in equation (4) above to become as follows. CF is a correction factor that accounts for the scatter from the jaws. CF equals zero at energies above 17 MeV and may reach 3% at 6 MeV.

\[
OF(X,Y) = OF(X,10) \cdot OF(Y,10) + CF(X,Y)
\]

5. **Sector integration method** Jursinic *et al* (1997) derived an empirical model to find the output of irregular shaped electron fields. The basic theory was to calculate the output in terms of previously measured factors for different energies and cones.

\[
Output = \frac{1}{16} \sum_{i=1}^{16} OF(E, SSD, cone, r_i)
\]

From the center of the cutout shape, 16 evenly spaced radii, \(r_i\), were used to characterize the insert, with the output determined as in equation (7). In order to find the summation factors for the radii, the output was measured for each E (electron energy) for each treatment cone at particular SSD using different circular inserts (\(r_i\)) and divided by the open cone output. Then, these results were plotted to form a curve of insert factors \(\frac{S_{ig}(r)}{S_{ig}(open\ cone)}\), where \(S_{ig}(r)\) and \(S_{ig}(open\ cone)\) are the outputs for the insert and open cones respectively. A polynomial fit was used to approximate the resultant insert factor values. In addition, Jursinic compared measured output with the calculated values and found that their method was accurate to within \(\pm 1\%\). However, this method works only for a fixed SSD.
Walker (1998) and Choi et al. (2000) extended the use of the sector integration method to predict the output from regular and irregular inserts with different SSDs. Since this project applies the results of their work, a detailed description will be given in chapter 3.

6. Monte Carlo method Zhang et al. (1999) used the Monte Carlo method to estimate the output for square cutouts on SSD=100 cm and SSD=120 cm. They achieved results within 1% of measured values. Beams from MD2 accelerator were simulated using the BEAM Monte Carlo code. Figure (13) has a diagram showing after simulation geometry of the beam coming out of the treatment head. However, Zhang did not discuss irregular inserts and how they could be treated. However, this technique looks promising since simulations of other machines have already been created. Kapur et al. (1998) performed similar work using Monte Carlo but for a Varian accelerator and SSD=100.0 cm.
7. **Two-Source method** Chen et al (2001) have recently published a mathematical model of relative output factors for electron beams. The formulation is based on Fermi-Eyges theory for an extended source. Two main contributions to dose deposition were considered: generalized effective source and cutout scattering. The dose in water could be calculated by summing the influence from both sources and using the pencil beam algorithm. The results were less than 1% of measured values. For large field sizes with cutout scattering ignored, this method leads to the same equations as in the square-root and one-dimensional methods.
The Varian model 2000CR and the 21EX with serial numbers (S/N) 951 and 1251 respectively were the two accelerators at Mary Bird Perkins Cancer Center used to collect the data. The two machines differ in some aspects. Whereas the 21EX produces 6 and 18 MV photons with high dose rate capability, the 2000CR produces 6 and 15 MV photons at a lower dose rate. Both accelerators produce 6, 9, 12, 16 and 20 MeV electron beams. Even though an electron energy beam from both machines may have the same $d_{\text{max}}$, the beam quality and characteristics may differ as shown in figures (14) and (15). That is the result of differences in beam production structures and the internal

![Figure 14. Depth dose curves for all electron energies for 21EX (S/N 1251)](image)

![Figure 15. Depth dose curves for all electron energies for 2000CR (S/N 951)](image)
parts of the treatment head. Both machines use the same technique for beam collimation, upper and lower independent jaws and electrons cones. All of the available cones, 6×6, 10×10, 15×15, 20×20 and 25×25 cm$^2$ were utilized. Tables (2-a and 2-b) list the values for the depth ionization properties mentioned in chapter 1 for the both accelerators.

Table 2 (a). The depth ionization curve characteristics for the 21EX (S/N 1251)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>d$_{\text{max}}$ (cm)</th>
<th>R$_p$ (cm)</th>
<th>R$_{50}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.3</td>
<td>2.85</td>
<td>2.27</td>
</tr>
<tr>
<td>9</td>
<td>1.8</td>
<td>4.28</td>
<td>3.49</td>
</tr>
<tr>
<td>12</td>
<td>2.8</td>
<td>5.93</td>
<td>4.93</td>
</tr>
<tr>
<td>16</td>
<td>3.4</td>
<td>7.75</td>
<td>6.43</td>
</tr>
<tr>
<td>20</td>
<td>2.2</td>
<td>9.88</td>
<td>8.17</td>
</tr>
</tbody>
</table>

Table 2 (b). The depth ionization curve characteristics for the 2000CR (S/N 951)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>d$_{\text{max}}$ (cm)</th>
<th>R$_p$ (cm)</th>
<th>R$_{50}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.3</td>
<td>2.70</td>
<td>2.31</td>
</tr>
<tr>
<td>9</td>
<td>2.0</td>
<td>3.60</td>
<td>3.23</td>
</tr>
<tr>
<td>12</td>
<td>2.8</td>
<td>5.09</td>
<td>4.83</td>
</tr>
<tr>
<td>16</td>
<td>3.3</td>
<td>6.65</td>
<td>6.43</td>
</tr>
<tr>
<td>20</td>
<td>2.2</td>
<td>8.63</td>
<td>8.83</td>
</tr>
</tbody>
</table>

Tap water was used as the medium to collect the data. There are several reasons for choosing water. First, TG-51 calibration protocol recommends using water. Second, the temperature of the medium that has direct contact with the radiation detector could be measured could be controlled. Third, sudden room temperature variation does not effect the measuring system instantly. The size of the water tank, or phantom, was 30×30×30 cm$^3$. The primary reason for using this large size was the space needed to insert the widest cone -25×25 cm$^2$ cone- when the SSD equaled 98.0 cm.

A small volume ionization chamber (0.14 cm$^3$) was the selected for dose measurement. For small inserts, the stem length and collection volume of the chamber
had to be small enough that the entire collecting volume was in a uniform field. The
technical description of the detector is listed in table (3)\textsuperscript{23}.

Table 3. The ion chamber characteristics

<table>
<thead>
<tr>
<th>S/N</th>
<th>Wall Material</th>
<th>Wall Thickness (mm)</th>
<th>Wall Density (g/cm\textsuperscript{3})</th>
<th>Cavity Radius (r_{\text{cav}}) (cm)</th>
<th>Nominal Volume (cm\textsuperscript{3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>Shonka C-552</td>
<td>0.4</td>
<td>1.76</td>
<td>0.300</td>
<td>0.140</td>
</tr>
</tbody>
</table>

Two electrometers were used to produce the voltage difference and read the
collected charge. They were manufactured by Keithley (Model #K-614), and calibrated
in January 2000 by M.D. Anderson Cancer Center Accredited Dosimetry Calibration
Laboratory. Temperature measurements were made with a Precision spirit-filled
thermometer, made by Cole-Parmer Instrument Co. It has excellent accuracy for
specific measurements (±0.2°C)\textsuperscript{24}. Pressure was measured by in house calibrated
barometer manufactured by Taylor Instrument Co. Model No.2250M.

The phantom was placed on the treatment couch and filled with water. Using
the optical distance indicator, the SSD was set to be 100 cm (Figure (16)). The SSD

![Figure 16. The water tank is raised to the correct SSD.](image)
was checked regularly with laser pointers or the standard metallic front pointer rod or mechanical distance indicator. The chamber was placed on the manual height controller (that served as the ion chamber holder at the same time) and brought to the surface of the water. The central axis of the chamber was lowered by \(0.5 \times r_{cav}\), \(r_{cav}\) is the radius of the camber collection cavity, because the effective point of measurement for cylindrical chambers is the distance “upstream” (figure (17)) \(^7\). The chamber was then lowered to the requested \(d_{max}\) by means of the manual height controller (Figure (18)). The SSD was changed by raising or lowering the treatment couch.

![Figure 17. The chamber is lowered 0.5\(\times r_{cav}\) along the central axis.](image1.png)

![Figure 18. The manual chamber holder used to change the chamber height precisely.](image2.png)

The thermometer was hung on the inner side of the filled tank. Ice cubes and cold water were added if the temperature was greater than 28.0°C. Measurements were not taken until the system reached equilibrium. The temperature was lowered because room temperature is about 22.5°C and the object was to have little or no change during data collection. Second, the barometer was kept outside of the room since the pressure changes little from inside to outside. To avoid false barometer readings, the barometer
glass was being tapped to make sure that the pointer was not stuck. Frequent
temperature and pressure readings were recorded during the data collection process.

The electrometer was connected to the chamber by a tri-axial cable extended to
the outside of the treatment room. The normal operating voltage of -300V DC (for
ionization chambers) was applied. The leakage current was measured prior to each use.
No measurements were taken unless this current was less than $3.0 \times 10^{-14}$ A.

Some initial preparation of the accelerator was required before starting any
measurements. The manufacturer-recommended warm up procedure was followed
prior to any irradiation. Internal pressure, temperature and cooling water level were
checked. As a part of the daily quality assurance procedure, the output of the machine
was checked with respect to the annual calibration. Each reading was taken for 300
MU. The dose rate used, amount of radiation delivered per unit time, was 1000
MU/min for the 21EX machine and 260 MU/min for the 2000CR. These dose rate
values were the maximum that could be set. The higher dose rate was selected for the
21EX in order to save time since measurements indicated very similar total dose
readings (~0.1 %) compared to 260 MU/min in the same accelerator. The gantry and
the collimator angles were set at $180^\circ$.

For each insert, two measurements were taken at 4 different SSDs. The average
value of the measurements was multiplied by temperature pressure correction (TPC)
(equation (8)). Thus, readings taken for open cones could be corrected for different

$$TPC = \frac{273.15 + T(^\circ C)}{295.15} \times \frac{760}{P(mmHg)}$$  \hspace{1cm} (8)$$

surrounding conditions and the air density. Figure (19) represents the system for the
open reading setup and figure (20) illustrates the reading for an insert, by showing the
beams eye view (BEV). The chamber was positioned along the center of the insert opening. In the case of rectangular inserts, the axis chamber was placed parallel to the long rectangle axis in the insert as shown in figure (20).

Figure 19. The BEV of the open insert in the 25×25 cm² cone  
Figure 20. The BEV of the 7×22 cm² insert in the 25×25 cm² cone

Circular inserts were also used in collecting data for this project. The inserts are manufactured by pouring the liquid form of cerrobend in the mold that has the insert, with the opening cut from the Styrofoam, in the middle and left to cool. The same thickness of insert was used for all energies. Inserts used for each cone are listed in table (4).

<table>
<thead>
<tr>
<th>Cone</th>
<th>Insert radius (cm) [IR=irregular]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6×6</td>
<td>2.0, 4.0, 5.0 and custom (IR and 3.0×5.0)</td>
</tr>
<tr>
<td>10×10</td>
<td>2.0, 4.0, 5.0, 6.0, 7.0, 8.0, custom (IR and 3.0×9.0)</td>
</tr>
<tr>
<td>15×15</td>
<td>2.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10.0, 12.0, custom (IR and 3.0×12.0)</td>
</tr>
<tr>
<td>20×20</td>
<td>2.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10.0, 12.0, 15.0, 18.0, custom (IR and 5.5×15.0)</td>
</tr>
<tr>
<td>25×25</td>
<td>2.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10.0, 12.0, 15.0, 18.0, 22.0, custom (23.0×25.0)</td>
</tr>
</tbody>
</table>

Table (5) illustrates a data collection record which lists energy, d_max, SSD, cone, insert size, electrometer reading, average, average×TPC, TPC and temperature and pressure tracking. Electrometer readings were not rounded since the display gives four significant figures. It should be noted that M the electrometer reading does not have
units since the electrometer display was not corrected by the electrometer correction factor to give the reading in $10^{-8}$ C.

According to TG-25, the output factor is calculated as shown in equation (9)

$$OF(F) = \frac{\frac{D}{U}(C_s, I_s)}{\frac{D}{U}(C_o, I_o)} \tag{9}$$

where $C_s$ and $C_o$ refer to treatment and reference cone sizes respectively. $I_s$ and $I_o$ refer to treatment inserts and the reference cone’s insert respectively. $\frac{D}{U}$ is the dose per monitor unit elsewhere (this thesis uses a different notation). In order to determine the insert factor, the cone ratio will be introduced in equation (9). Consequently, the output factor will be written as in equation (10) at a specific SSD. When the ISL is considered,

$$Output Factor = Cone Ratio \times Insert Factor \tag{10}$$

$D_{max}$ the dose rate at the depth of $d_{max}$ at the reference SSD=100cm, is related to $\dot{D}_{max}$ at another distance by the equation (11). Thus, equation (12) represents the output from a combination of an insert ($f$), cone ($C$), energy ($E$) and gap ($g$) or SSD. Two things

$$O(C, E, f, g) = O(C, E, f, g = 0) \times ISL(SSD_{eff}, d_{max}, g) \tag{12}$$
should be noted in the formula. First, the $SSD_{eff}$ is field size dependent (i.e. $f$ insert).

Second, it has been documented that inserts do not cause considerable change in $d_{max}$.

Moreover, the output shown above can be divided into two parts, the Insert Factor ($IF$) and Cone Ratio ($CR$). Thus, equation (12) is written as shown in equation (13).

$$OF(C, E, f, g) = IF(C, E, f, g = 0) \times CR(C, E, g = 0) \times \left(\frac{SSD_{eff}(C, E, f, d_{max}(E))}{SSD_{eff}(C, E, f, d_{max}(E) + g)}\right)^2$$ (13)

The inserts used may be categorized as square or irregular. The output for each type is expressed as follows.

i. For circular inserts,

$$OF(C, E, r, g) = IF(C, E, r, g = 0) \times CR(C, E, g = 0) \times \left(\frac{SSD_{eff}(C, E, r, d_{max}(E))}{SSD_{eff}(C, E, r, d_{max}(E) + g)}\right)^2$$ (14)

ii. For square inserts, an average radius is calculated by equation (15), which is derived from equating the areas of a square and the corresponding circle where $L$ is the side of the square.

$$L^2 = \pi r^2 ; \quad r = \sqrt{\frac{1}{\pi} \times L} = 0.564 \times L$$ (15)

iii. For all other inserts, equation (14) could be generalized to become as in (16).

The integration could be expressed as summation of infinite number of areas. However, the sector integration method used expresses this integration over as the irregular insert

$$OF(C, E, f, g) = \frac{\int_{0}^{\frac{\pi}{2}} IF(C, E, r(\theta), g = 0) \times CR(C, E, g = 0) \times \left(\frac{SSD_{eff}(C, E, r(\theta), d_{max}(E))}{SSD_{eff}(C, E, r(\theta), d_{max}(E) + g)}\right)^2 r_{i} d\theta}{\int_{0}^{\frac{\pi}{2}} d\theta}$$ (16)

as a summation terms of 16 radii. Consequently, equation (16) will be in the form shown in (17). Only the cone ratio was taken out of the summation since it is constant for a specific cone.
\[
CR(C, E, g = 0) \times \sum_{i=1}^{16} IF(C, E, r_i, g = 0) \times \left( \frac{SSD_{eff} (C, E, r_i, d_{max} (E))}{SSD_{eff} (C, E, r_i, d_{max} (E) + g)} \right)^2
\]

\[
\text{OF}(C, E, f, g) = \frac{16}{16}
\]

MUCalc (William Bice, PhD, IMPS, San Antonio, TX) is a Visual Basic program written by William Bice, PhD, was used to calculate the number monitor units needed to deliver the prescribed dose using different inserts at different situations (cones, energies…etc). The program requires fitting polynomial coefficients for insert factors at SSD=100.0 cm to be entered into a data file together with SSD_{eff} polynomial coefficients, cone ratios and d_{max}. The program prompts the user to choose the requested treatment machine, treatment cone, treatment energy and treatment SSD. The user has four options to enter the insert configuration. One, by drawing the shape using the mouse. Second, by digitizing the insert using the digitizer. Third, by choosing an input file of a previously defined irregular shape insert drawing. Fourth, by entering the dimensions using the keyboard for rectangular and square inserts. Appendix C is an example of results given by the program which shows the Windows (Microsoft Corporation, Redmond, WA) interface.

Microsoft EXCEL (Microsoft Corporation, Redmond, WA) spread sheets were used to find the least square fit for insert factor points. Also, EXCEL was used to re-check results obtained by the visual basic program. The SSD_{eff} for inserts listed above for each cone are plotted versus insert radii for each energy and cone. Mathematica (Wolfram Research, Inc., Champaign, IL) program was also used to fit the data, but its results were not used in the thesis.
A. Error Analysis

Three sources of uncertainty were considered: the barometer, the thermometer and the electrometer reading scales. Individual uncertainties were 0.001 mmHg for the pressure, 0.4°C error in temperature and 0.001 for the electrometer reading. The variance in the TPC value is in equation (18). The variance in insert factor with respect to the electrometer reading, which is multiplied by the TPC later, is equation (19). The variance in square root of the output ratios, used to find the SSD_{eff}, can be found in equation (20). The derivation of equations (18, 19 and 20) could be found in Appendix D. As discussed in chapter 1, SSD_{eff} can be obtained from the slope of a straight line.

\[
TPC \times \frac{0.64}{T + 273.15} \tag{18}
\]

to the electrometer reading, which is multiplied by the TPC later, is equation (19). The
\[
\sigma_{\text{IF}}^2 = \left( \frac{M_o}{M_g} \right)^2 \left[ \text{Var}(\text{TPC}_g) + \text{Var}(\text{TPC}_o) \right] \tag{19}
\]

variance in square root of the output ratios, used to find the SSD_{eff}, can be found in equation (20). The derivation of equations (18, 19 and 20) could be found in Appendix D. As discussed in chapter 1, SSD_{eff} can be obtained from the slope of a straight line.

\[
\sigma_{\sqrt{R}}^2 = \frac{1}{4} \left( \frac{M_o}{M_g} \right)^2 \left[ \text{Var}(\text{TPC}_g) + \text{Var}(\text{TPC}_o) \right] \tag{20}
\]

The variances for a slope (b) (i.e., \( y = bx + a \)) is given by equation (21), where \( r \) is the coefficient of correlation for the line. For the differences between the measured and the calculated values is calculated by Equation (22).

\[
\sigma^2(b) = \frac{(1-r^2) \sum (y-\bar{y})^2}{N-2} \times \frac{1}{\sum (x-\bar{x})^2} \tag{21}
\]

\[
\% \text{ error} = \frac{\text{measured} - \text{calculated}}{\text{calculated}} \times 100 \tag{22}
\]
CHAPTER 4
RESULTS AND DISCUSSION

Positive integer power (0 to 6) polynomials were used to create the least squares fits for SSD$_{\text{eff}}$ and insert factors as functions of the insert radii. Excel was used. For illustration, spline fits were constructed using Mathematica for two cases of SSD$_{\text{eff}}$ and insert factors.

A. Effective Source to Surface Distance

Figure (21) shows a plot made by the author to find the SSD$_{\text{eff}}$ for 6 MeV for the 21EX (S/N 1251) machine using 6×6 cm$^2$ open cone insert. Four points were generated even though only two are required for any line within those two points. This was done to minimize statistical error related to the machine output, the charge collection, and couch position. Using equation (2), the SSD$_{\text{eff}}$ is obtained from the plot in figure (21).

\[
y = 0.014x + 1.00 \\
\text{r}^2 = 0.999 \\
\text{SSD}_{\text{eff}} = (\text{slope})^{-1} - d_{\text{max}} \\
\text{SSD}_{\text{eff}} = (0.014)^{-1} - 1.3 = 70.13 \text{ cm}
\]

![Figure 21. 21EX (S/N 1251) SSD$_{\text{eff}}$; 6 MeV; 6×6 cm$^2$ open cone](image)

It is found that the SSD$_{\text{eff}}$ changes with energy, cone size and cutout size $^1$. The variances in SQRT(Mo/Mg) were not included since they are very small compared to the SSD$_{\text{eff}}$ values. An example is shown below using equations (18) and (20). The
correlation coefficient for this line was 0.999, so the variance in the slope is very small 
\[(1-r^2 = 0.0)\text{ in equation (21)}\].

\[
T = 22.2^\circ C; TPC = 0.993; Var(TPC) = 0.002
\]

\[
\left(\frac{M_o}{M_g}\right)^2 = 1.051 \; ; \; Var\left(\frac{M_o}{\sqrt{M_g}}\right) = 0.25 \times 1.051 \times 2 \times 0.002 = 0.001
\]

Polynomial fits for SSD_{eff} were created for all inserts for each energy. Thus, SSD_{eff} is insert-size and energy dependent for a specific accelerator. When figures (22) and (23) are compared (as an example), SSD_{eff} values are very close for the 21EX and the 2000CR accelerators. That was also the case for results obtained earlier by Mendez (2001) for the 21EX (S/N 1421) and the 2100C (S/N 90) linacs using similar methods and inserts \(^{27}\). The 2100C has type II cones which are different in shape and structure than the type III used by the 21EX and the 2000CR. An example of fitting using the Mathematica program is in Appendix E.

![Figure 22. The SSD_{eff} values of 12 MeV for the 2000CR (S/N 951). The fitting is: SSD_{eff}(r) = -7.92 \times 10^{-4} r^6 + 3.8 \times 10^{-2} r^5 - 7.23 \times 10^{-1} r^4 + 6.93 r^3 - 3.51 \times 10 r^2 + 9.14 \times 10 r - 13.4 \text{ with } r^2 = 0.99](image-url)
Table (6-a) lists the SSD eff values for both machines used in this project and another one used by Mendez (2001) the 21EX (S/N 1421) at 16 MeV. There are some differences in these results. This may be the result of different structures in the treatment head. Both 21EX machines are identical with regard to internal structure, but the 21EX (S/N 1421) has an MLC for photon collimation. The 2000CR is a refurbished machine so the internal structure may be slightly different. As a result, the electrons may experience a different scattering environment. This, of course, is described by the model and is acceptable and valid for use. The differences may be explained by considering two points. Firstly, SSD eff often is not exactly reproducible. The author compared the results of open cones with the data currently used and there was a small difference as shown in table (7). Secondly, the output of the machines changes from time to time, ±2% is an acceptable range; this may be due to energy or steering drifts over time. This was experienced by the author. However, the SSD eff values were noticeably different for the 2100C as shown in table (6-b). Appendices (A&B) have the remainder of the results for the 21EX (S/N 1251) and the 2000CR (S/N 951).

![Graph](image)

Figure 23. The SSD eff values of 12 MeV for the 21EX (S/N 1251). The fitting is: $SSD_{eff}(r) = -5.66 \times 10^{-4} r^6 + 2.81 \times 10^{-2} r^5 - 5.57 \times 10^{-1} r^4 + 5.58 r^3 - 2.97 \times 10 r^2 + 8.13 \times 10 r - 6.57$ $r^2 = 0.99$
### Table 6-a. The calculated SSD\(_{\text{eff}}\) values of 16 MeV for three machines: 21EX (S/N 1251), 21EX (S/N 1421) and 2000CR(S/N 951)

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>6x6 cm(^2) cone</th>
<th>10x10 cm(^2) cone</th>
<th>15x15 cm(^2) cone</th>
<th>20x20 cm(^2) cone</th>
<th>25x25 cm(^2) cone</th>
<th>Ave.</th>
<th>STD</th>
<th>SSD(_{\text{eff}})/Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N</td>
<td>1251</td>
<td>1421</td>
<td>951</td>
<td>1251</td>
<td>1421</td>
<td>951</td>
<td>1251</td>
<td>1421</td>
</tr>
<tr>
<td>1.0</td>
<td>21.1</td>
<td>20.9</td>
<td>23.7</td>
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<td>32.7</td>
<td>36.5</td>
<td>34.8</td>
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<td>33.1</td>
<td>30.9</td>
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<td>51.2</td>
<td>54.2</td>
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<td>53.1</td>
<td>50.2</td>
<td>46.2</td>
</tr>
<tr>
<td>2.5</td>
<td>62.2</td>
<td>58.7</td>
<td>64.0</td>
<td>64.5</td>
<td>59.8</td>
<td>66.6</td>
<td>63.4</td>
<td>58.8</td>
</tr>
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<td>3.0</td>
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<td>69.2</td>
<td>73.3</td>
<td>72.7</td>
<td>69.2</td>
</tr>
<tr>
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<td>78.7</td>
<td>76.9</td>
<td>79.1</td>
<td>78.1</td>
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<td>78.6</td>
<td>75.7</td>
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<td>81.6</td>
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<td>82.3</td>
<td>81.7</td>
</tr>
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<td>84.5</td>
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<td>84.3</td>
<td>84.6</td>
<td>86.7</td>
<td>83.5</td>
</tr>
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<td>85.0</td>
<td>84.9</td>
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<td>86.5</td>
<td>86.6</td>
<td>88.0</td>
<td>85.8</td>
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<td>90.5</td>
<td>90.1</td>
<td>92.8</td>
<td>90.5</td>
<td>90.1</td>
<td>92.8</td>
<td>90.5</td>
</tr>
<tr>
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<td>92.7</td>
<td>92.3</td>
<td>92.6</td>
<td>93.6</td>
<td>92.3</td>
<td>92.6</td>
<td>92.7</td>
<td>0.5</td>
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<tr>
<td>11.0</td>
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<td>94.0</td>
<td>94.2</td>
<td>93.8</td>
<td>94.0</td>
<td>93.8</td>
<td>1.4</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### Table 6-b. The calculated SSD\(_{\text{eff}}\) values of 16 MeV for 2100C (S/N 90)

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>6x6 cone</th>
<th>10x10 cone</th>
<th>15x15 cone</th>
<th>20x20 cone</th>
<th>25x25 cone</th>
<th>Average</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>32.60</td>
<td>32.60</td>
<td>28.90</td>
<td>30.80</td>
<td>30.50</td>
<td>31.08</td>
<td>1.56</td>
</tr>
<tr>
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<td>45.10</td>
<td>45.10</td>
<td>46.00</td>
<td>45.50</td>
<td>44.10</td>
<td>45.16</td>
<td>0.70</td>
</tr>
<tr>
<td>2.5</td>
<td>55.60</td>
<td>55.30</td>
<td>56.20</td>
<td>57.30</td>
<td>52.60</td>
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<td>1.74</td>
</tr>
<tr>
<td>3.0</td>
<td>65.80</td>
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<td>62.90</td>
<td>68.40</td>
<td>3.84</td>
</tr>
<tr>
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<td>71.80</td>
<td>69.70</td>
<td>62.90</td>
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<td>68.83</td>
<td>1.70</td>
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<td>75.10</td>
<td>67.80</td>
<td>73.15</td>
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<td></td>
</tr>
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<td>5.0</td>
<td>79.50</td>
<td>80.10</td>
<td>76.90</td>
<td>78.83</td>
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<td>1.40</td>
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<td>84.30</td>
<td>82.87</td>
<td>84.30</td>
<td>84.30</td>
<td>2.76</td>
</tr>
<tr>
<td>7.5</td>
<td>85.80</td>
<td>89.70</td>
<td>87.75</td>
<td>87.75</td>
<td>87.75</td>
<td>87.75</td>
<td></td>
</tr>
<tr>
<td>9.0</td>
<td>88.70</td>
<td>92.10</td>
<td>90.40</td>
<td>90.40</td>
<td>90.40</td>
<td>90.40</td>
<td>2.40</td>
</tr>
<tr>
<td>11.0</td>
<td>96.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7. Comparison between in-use and thesis SSD_{eff} values for 2000CR(S/N 951) and 21EX (S/N 1251) for 16 MeV (open insert)

| S/N | 6x6 cone in-use | 10x10 cone in-use | 15x15 cone in-use | 20x20 cone in-use | 25x25 cone in-use | 6x6 cone thesis | 10x10 cone thesis | 15x15 cone thesis | 20x20 cone thesis | 25x25 cone thesis |
|-----|----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| S/N | 1251           | 951             | 1251            | 951             | 1251           | 951            | 1251           | 951            | 1251           | 951            | 1251           | 951            |
| SSD_{eff} in-use | 87.6     | 83.8            | 86.0            | 87.0            | 89.6           | 91.9           | 92.0           | 95.5           | 91.6           | 93.4           |
| SSD_{eff} thesis  | 84.6     | 83.6            | 87.0            | 86.5            | 92.3           | 91.1           | 93.8           | 90.6           | 94.1           | 93.7           |

\[ \frac{\text{SSD}_{\text{eff}} \text{thesis}}{\text{SSD}_{\text{eff}} \text{ in-use}} \times 100 \]

\[
\begin{array}{cccccccc}
3.42 & 0.24 & 1.16 & 0.57 & 3.01 & 0.87 & 1.96 & 5.13 & 2.73 & 0.32 \\
\end{array}
\]

Figures (24) and (25) show the resultant SSD_{eff} for the 2000CR for 16 MeV, from data were collected two days apart. The locations of some points are different when both figures are compared. This difference should not be considered typical, but is indicative of the dependence of theses results on proper tuning, stability and probably

![Figure 24. 2000CR (S/N 951); 20 MeV, SSD_{eff} values spread on 10/6/01.](image)

![Figure 25. 2000CR (S/N 951); 20 MeV, SSD_{eff} values spread on 10/8/01.](image)
the influence of the collimator opening. The accelerator was not running smoothly on 10/6, even though the output and the daily QA were reasonable. The data in figure (25) were used in the calculation because they were collected after the maintenance was completed. Given this, note that the ISL is relatively insensitive to the value of SSD_eff. A small difference will not affect in the results. For example, let us consider two values of SSD_eff, 65.78 cm and 63.15 cm for which d_max equals 1.2 cm and the gap = 2.0 cm. The SSD_eff tends to increase with insert size. However, this trend is not strictly adhering to for larger inserts and different beam energies as shown in figure (23).

B. Insert Factors

Insert factors change with air gap, energy and insert size. This change is relatively smooth and modeled well by a polynomial fit. Insert factors approach unity for large inserts, for any combination of cone size, energy and SSD as shown in figure (26), table (8) lists the values used to create the curves.

\[
\left(\frac{65.78 + 1.2}{65.78 + 1.2 + 2}\right)^2 = 0.94 \quad \text{compared to} \quad \left(\frac{63.15 + 1.2}{63.15 + 1.2 + 2}\right)^2 = 0.94
\]

![Figure 26. 21EX(S/N 1251); 6 MeV; Insert factors for 15×15 cm² cone inserts](image-url)
In order to pass through every data point, a 6th order polynomial was used to model the insert factors results. While this made the line matches the fitted results quite nicely, there were some unintended consequences: the polynomial fit could not relatively be used to extrapolate the data and even between some data points, particularly high energies and large radii, the polynomial gave unreasonable results. An example of this is shown in figure (27). Note the sudden increase after insert size 11.0 cm. That increase is not reasonable and caused by the polynomial fitting. In order to

<table>
<thead>
<tr>
<th>Insert radius (cm)</th>
<th>gap = -2.0 cm</th>
<th>gap = 0 cm</th>
<th>gap = 5.0 cm</th>
<th>gap = 10.0 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.777</td>
<td>0.710</td>
<td>0.532</td>
<td>0.395</td>
</tr>
<tr>
<td>1.5</td>
<td>0.915</td>
<td>0.886</td>
<td>0.778</td>
<td>0.646</td>
</tr>
<tr>
<td>2.0</td>
<td>0.989</td>
<td>0.972</td>
<td>0.923</td>
<td>0.846</td>
</tr>
<tr>
<td>2.5</td>
<td>1.012</td>
<td>1.001</td>
<td>0.972</td>
<td>0.933</td>
</tr>
<tr>
<td>3.0</td>
<td>1.024</td>
<td>1.018</td>
<td>0.998</td>
<td>0.978</td>
</tr>
<tr>
<td>3.5</td>
<td>1.017</td>
<td>1.011</td>
<td>0.998</td>
<td>0.984</td>
</tr>
<tr>
<td>4.0</td>
<td>1.013</td>
<td>1.011</td>
<td>1.004</td>
<td>0.996</td>
</tr>
<tr>
<td>5.0</td>
<td>1.008</td>
<td>1.007</td>
<td>1.003</td>
<td>1.000</td>
</tr>
<tr>
<td>6.0</td>
<td>1.006</td>
<td>1.005</td>
<td>1.000</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Table 8. The measured insert factors for the 21EX (S/N 1251); 6 MeV; 15×15 cm² cone inserts

Figure 27. 21EX(S/N 1251); 6 MeV; Insert factors for 25×25 cm² cone inserts
solve this problem, a cutoff radius was chosen for each energy and cone combination
above which insert factors are set to 1.0, regardless of treatment SSD (Table (9)).

Table 9. The insert radius limits for fitted insert factors.

<table>
<thead>
<tr>
<th>Cone Size</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6×6 cm²</td>
<td>6 9 12 16 20</td>
</tr>
<tr>
<td>6×10 cm²</td>
<td>4.0 cm 4.0 cm 4.0 cm 4.0 cm 5.0 cm</td>
</tr>
<tr>
<td>10×15 cm²</td>
<td>6.0 cm 5.0 cm 5.0 cm 6.0 cm 6.5 cm</td>
</tr>
<tr>
<td>20×20 cm²</td>
<td>6.0 cm 6.0 cm 6.5 cm 9.0 cm 9.5 cm</td>
</tr>
<tr>
<td>25×25 cm²</td>
<td>6.0 cm 6.0 cm 9.0 cm 8.5 cm 11.0 cm</td>
</tr>
</tbody>
</table>

Figure (28) is an example of an insert factor curve with the variances shown.

The variance calculation is shown below using equations (18 and 19). An example for
fitting using the Mathematica program is in Appendix E. Analogous to the SSD_{eff}
results, insert factors are not exactly reproducible. They are similarly dependent on
scattering and machine stability. The rest of curves for machines used in the project are
found in appendices A and B.

\[
T = 22.2^\circ C; TPC = 0.993; \text{Var}(TPC) = 0.002
\]

\[
\left(\frac{M_g}{M_o}\right)^2 = 0.571; \text{Var}\left(\frac{M_g}{M_o}\right) = 0.571 \times 2 \times 0.002 = 0.002
\]
Some of the custom and rectangular inserts were used to verify the predicted insert factors on the 21EX (S/N 1251) machine. The shape of these custom inserts were digitized in MUCalc which determines the sector lengths as shown in figure (29). Table (10-a) lists the results for insert factors corresponding to SSD=100 cm and SSD=105.0 cm, for various energies, and these are compared with MUCalc results.

It was subsequently determined that both machines have very similar insert factors for these inserts which would imply that both could use the same insert factor model (Table (10-b)). As another check of the program results, independent measurements of insert sectors are made by hand as shown in table (10-a). The difference (error) between measurements insert factors and calculated is small ($\approx \pm 2.0\%$) which agrees with results found by Walker who used Siemens and Philips machines and Mendez (2001) who used two Varian machines\textsuperscript{16&25}.

![Figure 29. The integration segments shown for some inserts used in the measurements. (William Bice, PhD, IMPS, San Antonio, TX)]
Table 10-a. Comparison of the measured insert factors and those calculated with MUCalc for the 21EX (S/N 1251)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Cone</th>
<th>Insert</th>
<th>Measured</th>
<th>MUCalc</th>
<th>% error</th>
<th>Measured</th>
<th>MUCalc</th>
<th>% error</th>
<th>Hand Calculated</th>
<th>SSD&lt;sub&gt;eff&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 MeV</td>
<td>6×6</td>
<td>3.0×5.0</td>
<td>0.948</td>
<td>0.945</td>
<td>0.34</td>
<td>0.927</td>
<td>0.945</td>
<td>-1.92</td>
<td>65.78</td>
<td>63.15</td>
</tr>
<tr>
<td>12 MeV</td>
<td>6×6</td>
<td>3.0×5.0</td>
<td>0.936</td>
<td>0.925</td>
<td>1.13</td>
<td>0.931</td>
<td>0.926</td>
<td>0.61</td>
<td>75.36</td>
<td>73.85</td>
</tr>
<tr>
<td>16 MeV</td>
<td>6×6</td>
<td>3.0×5.0</td>
<td>0.951</td>
<td>0.944</td>
<td>0.76</td>
<td>0.948</td>
<td>0.943</td>
<td>0.49</td>
<td>80.39</td>
<td>79.39</td>
</tr>
<tr>
<td>20 MeV</td>
<td>6×6</td>
<td>3.0×5.0</td>
<td>1.000</td>
<td>1.002</td>
<td>-1.06</td>
<td>0.999</td>
<td>1.010</td>
<td>-1.12</td>
<td>75.77</td>
<td>74.87</td>
</tr>
<tr>
<td>9 MeV</td>
<td>10×10</td>
<td>3.0×9.0</td>
<td>0.948</td>
<td>0.943</td>
<td>0.51</td>
<td>0.923</td>
<td>0.940</td>
<td>-1.82</td>
<td>74.58</td>
<td>67.50</td>
</tr>
<tr>
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<td>10×10</td>
<td>3.0×9.0</td>
<td>0.935</td>
<td>0.923</td>
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<td>0.929</td>
<td>0.922</td>
<td>0.73</td>
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<td>75.71</td>
</tr>
<tr>
<td>16 MeV</td>
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<td>3.0×9.0</td>
<td>0.945</td>
<td>0.936</td>
<td>0.90</td>
<td>0.940</td>
<td>0.936</td>
<td>0.41</td>
<td>83.74</td>
<td>80.24</td>
</tr>
<tr>
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<td>3.0×9.0</td>
<td>0.996</td>
<td>0.997</td>
<td>-0.11</td>
<td>0.989</td>
<td>0.997</td>
<td>-0.87</td>
<td>80.45</td>
<td>76.61</td>
</tr>
<tr>
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<td>1.000</td>
<td>0.22</td>
<td>0.998</td>
<td>1.000</td>
<td>-0.12</td>
<td>81.08</td>
<td>80.70</td>
</tr>
<tr>
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<td>1.000</td>
<td>0.30</td>
<td>1.000</td>
<td>1.000</td>
<td>0.0</td>
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<td>85.16</td>
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<tr>
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<td>0.998</td>
<td>0.14</td>
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<td>0.997</td>
<td>0.998</td>
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<td>86.30</td>
</tr>
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<td>1.006</td>
<td>0.0</td>
<td>1.004</td>
<td>1.006</td>
<td>-0.13</td>
<td>83.06</td>
<td>82.72</td>
</tr>
<tr>
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<td>custom</td>
<td>1.001</td>
<td>1.005</td>
<td>-0.45</td>
<td>0.989</td>
<td>1.005</td>
<td>-1.60</td>
<td>80.63</td>
<td>77.11</td>
</tr>
<tr>
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<td>1.000</td>
<td>-0.87</td>
<td>0.977</td>
<td>1.000</td>
<td>-2.33</td>
<td>83.82</td>
<td>82.10</td>
</tr>
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<td>custom</td>
<td>0.980</td>
<td>0.994</td>
<td>-1.46</td>
<td>0.973</td>
<td>0.993</td>
<td>-2.06</td>
<td>85.03</td>
<td>84.76</td>
</tr>
<tr>
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<td>0.996</td>
<td>-1.09</td>
<td>0.978</td>
<td>0.996</td>
<td>-1.86</td>
<td>86.58</td>
<td>86.25</td>
</tr>
<tr>
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<td>custom</td>
<td>1.016</td>
<td>1.018</td>
<td>-0.24</td>
<td>1.004</td>
<td>1.018</td>
<td>-1.33</td>
<td>83.25</td>
<td>82.30</td>
</tr>
<tr>
<td>6 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.010</td>
<td>1.005</td>
<td>0.48</td>
<td>1.001</td>
<td>1.005</td>
<td>-0.40</td>
<td>83.67</td>
<td>82.47</td>
</tr>
<tr>
<td>9 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.009</td>
<td>1.003</td>
<td>0.59</td>
<td>1.000</td>
<td>1.003</td>
<td>-0.30</td>
<td>86.19</td>
<td>85.55</td>
</tr>
<tr>
<td>12 MeV</td>
<td>20×20</td>
<td>custom</td>
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<td>1.003</td>
<td>0.40</td>
<td>0.999</td>
<td>1.003</td>
<td>-0.33</td>
<td>86.87</td>
<td>86.95</td>
</tr>
<tr>
<td>16 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.008</td>
<td>1.009</td>
<td>-0.08</td>
<td>1.001</td>
<td>1.009</td>
<td>-0.73</td>
<td>88.23</td>
<td>87.91</td>
</tr>
<tr>
<td>20 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.024</td>
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<td>0.0</td>
<td>1.013</td>
<td>1.024</td>
<td>-1.05</td>
<td>84.87</td>
<td>84.38</td>
</tr>
<tr>
<td>6 MeV</td>
<td>25×25</td>
<td>6.0×23.0</td>
<td>1.005</td>
<td>1.003</td>
<td>0.15</td>
<td>0.918</td>
<td>1.005</td>
<td>-0.91</td>
<td>87.05</td>
<td>83.57</td>
</tr>
<tr>
<td>9 MeV</td>
<td>25×25</td>
<td>6.0×23.0</td>
<td>1.009</td>
<td>1.004</td>
<td>0.44</td>
<td>0.999</td>
<td>1.004</td>
<td>-0.47</td>
<td>86.18</td>
<td>88.70</td>
</tr>
</tbody>
</table>
Table 10-b. Comparison of the measured insert factors and SSD\textsubscript{eff} values for the 21EX (S/N 1251) and the 2000CR (S/N 951)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Cone</th>
<th>Insert</th>
<th>IF at SSD =100 cm</th>
<th>IF at SSD =105 cm</th>
<th>SSD\textsubscript{eff} (cm) and ISL (gap = 10.0 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 MeV</td>
<td>6x6</td>
<td>3.0×5.0</td>
<td>0.941</td>
<td>0.945</td>
<td>65.55 0.76</td>
</tr>
<tr>
<td>12 MeV</td>
<td>6x6</td>
<td>3.0×5.0</td>
<td>0.937</td>
<td>0.925</td>
<td>73.56 0.78</td>
</tr>
<tr>
<td>16 MeV</td>
<td>6x6</td>
<td>3.0×5.0</td>
<td>0.953</td>
<td>0.944</td>
<td>77.77 0.79</td>
</tr>
<tr>
<td>20 MeV</td>
<td>6x6</td>
<td>3.0×5.0</td>
<td>1.001</td>
<td>1.002</td>
<td>76.35 0.79</td>
</tr>
<tr>
<td>9 MeV</td>
<td>10×10</td>
<td>3.0×9.0</td>
<td>0.939</td>
<td>0.943</td>
<td>68.88 0.77 63.15 0.75</td>
</tr>
<tr>
<td>12 MeV</td>
<td>10×10</td>
<td>3.0×9.0</td>
<td>0.936</td>
<td>0.923</td>
<td>75.28 0.79 75.71 0.79</td>
</tr>
<tr>
<td>16 MeV</td>
<td>10×10</td>
<td>3.0×9.0</td>
<td>0.945</td>
<td>0.936</td>
<td>78.82 0.79 80.24 0.80</td>
</tr>
<tr>
<td>20 MeV</td>
<td>10×10</td>
<td>3.0×9.0</td>
<td>0.996</td>
<td>0.997</td>
<td>77.13 0.79 76.61 0.79</td>
</tr>
<tr>
<td>6 MeV</td>
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<td>custom</td>
<td>1.002</td>
<td>1.000</td>
<td>81.14 0.80 80.70 0.79</td>
</tr>
<tr>
<td>9 MeV</td>
<td>10×10</td>
<td>custom</td>
<td>1.001</td>
<td>1.000</td>
<td>83.41 0.80 85.16 0.80</td>
</tr>
<tr>
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<td>84.71 0.81 85.36 0.81</td>
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<tr>
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<td>custom</td>
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<td>0.997</td>
<td>85.55 0.81 86.30 0.81</td>
</tr>
<tr>
<td>20 MeV</td>
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<td>1.005</td>
<td>1.006</td>
<td>82.05 0.80 82.72 0.80</td>
</tr>
<tr>
<td>6 MeV</td>
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<td>custom</td>
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<td>1.005</td>
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<td>1.000</td>
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<tr>
<td>12 MeV</td>
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<td>0.994</td>
<td>83.14 0.80 84.76 0.81</td>
</tr>
<tr>
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<td>15×15</td>
<td>custom</td>
<td>1.000</td>
<td>0.996</td>
<td>85.01 0.81 86.25 0.81</td>
</tr>
<tr>
<td>20 MeV</td>
<td>15×15</td>
<td>custom</td>
<td>1.016</td>
<td>1.018</td>
<td>82.14 0.80 82.30 0.80</td>
</tr>
<tr>
<td>6 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.000</td>
<td>1.005</td>
<td>82.47 0.80 82.47 0.80</td>
</tr>
<tr>
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<td>20×20</td>
<td>custom</td>
<td>1.001</td>
<td>1.003</td>
<td>86.06 0.81 85.55 0.81</td>
</tr>
<tr>
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<td>20×20</td>
<td>custom</td>
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<td>1.003</td>
<td>86.27 0.81 86.95 0.81</td>
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<tr>
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<td>20×20</td>
<td>custom</td>
<td>1.016</td>
<td>1.009</td>
<td>87.05 0.81 87.91 0.81</td>
</tr>
<tr>
<td>20 MeV</td>
<td>20×20</td>
<td>custom</td>
<td>1.023</td>
<td>1.024</td>
<td>84.48 0.80 84.38 0.80</td>
</tr>
<tr>
<td>6 MeV</td>
<td>25×25</td>
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<td>1.005</td>
<td>1.003</td>
<td>82.76 0.80 83.57 0.80</td>
</tr>
<tr>
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<td>6.0×23.0</td>
<td>1.008</td>
<td>1.004</td>
<td>84.40 0.80 88.70 0.81</td>
</tr>
</tbody>
</table>
C. MUCalc Calculations

In order to give an example of the MUCalc formalism, suppose the radiation oncologist prescribes 200 cGy to be delivered to the $d_{\text{max}}$ using 9 MeV and a rectangular insert ($10 \times 16$ cm$^2$) and $20 \times 20$ cm$^2$ cone, using the 21EX (S/N 1251) machine with a treatment SSD of 102.0 cm. MUCalc applies equations (23) for the dose rate and (24) for monitor units needed. It is noted that $SSD_{\text{eff}}$ of the open cone is used in the ISL instead of the applying the ISL for each radius. MUCalc calculates in both ways but it gives the results using equation (23) and shows the percentage difference of both methods. $D$ is the dose rate (cGy/MU), the reference output is 1.00 cGy/MU and $D_p$ is the dose prescribed by the physician. CR is the previously measured cone ratio, 0.995 in this case, at 100.0 cm SSD. $ISL(SSD_{\text{eff}}, cone, g , d_{\text{max}})$ is the inverse square law using the gap, 102-100 = 2.0 cm, and the $SSD_{\text{eff}}$ for the insert at 9 MeV, $d_{\text{max}}$=1.8 cm. $IF(f)$ is the insert factor at 100.0 cm SSD, equals to 1.003 from the model.

$$D(9\text{MeV},10 \times 16,20 \times 20,102) = 1.0 \times 0.995 \times \left( \frac{93.45 + 1.8}{93.45 + 1.8 + 2} \right)^2 \times 1.003 = 0.957$$

$$MU = \frac{200}{0.957} = 209$$

The MUCalc program calculates the insert factors and the $SSD_{\text{eff}}$ values using the coefficients of the corresponding fitting polynomials. These coefficients are entered manually in a data file. The radii from a custom insert were determined. Those radii are
used to generate the insert factor at 100.0 cm SSD and the SSD_{eff} for a combination of energy, cone and SSD independently from MUCalc. That was done to make sure that the program uses the correct values. Table (11) shows an example for that and Appendix C has the output of MUCalc program together with the shape of the insert used. MUCalc has slight different terminology as following: Radial Distance means radius length in cm, Electron Blocking Factors means Insert Factor, Virtual Source Distance means SSD_{eff} in cm, and Non-linear EBF/VSD means ISL×IF.

Table 11. MUCalc program calculation step by step check for 2000CR; 6MeV; 6×6 cm² cone using a custom insert.

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>IF</th>
<th>SSD_{eff}</th>
<th>ISL</th>
<th>ISL×IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.20829</td>
<td>0.9911608</td>
<td>56.14126</td>
<td>0.8462615</td>
<td>0.8387812</td>
</tr>
<tr>
<td>2.23419</td>
<td>0.9927231</td>
<td>56.70539</td>
<td>0.8475812</td>
<td>0.8414134</td>
</tr>
<tr>
<td>2.399416</td>
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<td>0.8552898</td>
<td>0.8553874</td>
</tr>
<tr>
<td>2.207201</td>
<td>0.9910562</td>
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<td>0.8461755</td>
<td>0.8386074</td>
</tr>
<tr>
<td>1.75866</td>
<td>0.9386850</td>
<td>44.84788</td>
<td>0.8140447</td>
<td>0.7641315</td>
</tr>
<tr>
<td>1.31522</td>
<td>0.8258047</td>
<td>31.09580</td>
<td>0.7504673</td>
<td>0.6197394</td>
</tr>
<tr>
<td>1.886937</td>
<td>0.9590168</td>
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<td>0.8253050</td>
<td>0.7914814</td>
</tr>
<tr>
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<td>0.9940651</td>
<td>57.22278</td>
<td>0.8487717</td>
<td>0.8437343</td>
</tr>
<tr>
<td>2.343717</td>
<td>0.9981277</td>
<td>59.05922</td>
<td>0.8528517</td>
<td>0.8512549</td>
</tr>
<tr>
<td>2.380316</td>
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<td>59.81650</td>
<td>0.8544708</td>
<td>0.8540321</td>
</tr>
<tr>
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<td>0.7880426</td>
</tr>
<tr>
<td>1.592361</td>
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<td>0.7957500</td>
<td>0.7198909</td>
</tr>
<tr>
<td>1.500103</td>
<td>0.8816807</td>
<td>37.17131</td>
<td>0.7831925</td>
<td>0.6905256</td>
</tr>
<tr>
<td>1.48479</td>
<td>0.8775615</td>
<td>36.68721</td>
<td>0.7809016</td>
<td>0.6852891</td>
</tr>
<tr>
<td>1.699373</td>
<td>0.9276002</td>
<td>43.16872</td>
<td>0.8080680</td>
<td>0.7495641</td>
</tr>
<tr>
<td>1.859981</td>
<td>0.9551403</td>
<td>47.61018</td>
<td>0.8231082</td>
<td>0.7861839</td>
</tr>
<tr>
<td>Average</td>
<td>0.9495873</td>
<td>48.87715</td>
<td>0.8222573</td>
<td>0.7823787</td>
</tr>
</tbody>
</table>

D. Changes in Output

For electron irradiation the primary cause for changes of output with SSD and with insert is a change in the scattering configuration. When the SSD_{eff} values are studied, it will be seen that they reach values of 98.0 cm as high. That contradicts with the assumption of the scattering foils as the source for the electron beam since they are
located at a shorter distance (87.5 cm). This means that scattering from the head, cones, insert sides and jaws as well as scattering foils all contribute in the electron fluence reaching the chamber 16. Photons have scattering also but the changes due to jaws settings and blocks are not as complicated as for electrons. That could be explained when we compare dose deposition by electrons and photons. Whereas dose deposition from photons mainly comes from the primary beam, electron beams suffer significant scattering, so that a large fraction of the energy is deposited by the scattered electrons. More specifically, sources of scattering differ from one insert shape to another, and for different cone sizes and jaws settings (figure (30)). Also, figure (31) shows another picture of scattering from all sources obtained by the BEAM program simulation 20.

Figure 30. The insert side scattering effect on the radiation delivery with cross of the insert indicated.

Figure 31. The 9 MeV electron beam from Varian 2100C with type II applicator as shown by EGS-windows with about 100 histories. [Taken form Reference (20)]
In electron dosimetry, the conventional nominal target to surface distance (TSD) cannot be used for inverse square correction. Instead, an effective source to surface distance is used to predict geometrical losses. The SSD\textsubscript{eff} is very dependent on cone, insert size and shape and energy. Machines from the same vendor with similar linac head structures have very close SSD\textsubscript{eff} values assuming that main beam characteristics are same (e.g. d\textsubscript{max}… etc).

Electron cutouts affect the radiation output reaching the patient, so insert factors are introduced to correct for the radiation delivery amount. Inserts can increase the output by as much as 2% or decrease it by as much as 40%. As expected, as the insert radius grows, the impact on output becomes less. Like SSD\textsubscript{eff}, the insert factors for accelerators from the same vendor and having similar depth dose curves can be are very similar. Insert factors do not have effects on the radiation output for large inserts at any SSD.

The modified sector integration method can be used to predict output factors of various shapes and different treatment SSDs, but it requires an extensive amount of work to collect sufficient data to properly model. Indicative of this, Choi, et al., used only two cones in and a limited energy range (8, 10 and 12 MeV)\textsuperscript{17}. Finding a way to reduce the number of measurements while keeping the accuracy acceptable would be a significant improvement in using this method.
First principle computational methods such as Monte Carlo look promising, since they could be used to produce a “general” table for all the machines made by the same company. However, Monte Carlo, takes considerable amount of time and efforts in the initial model setup, but is supposed to be more reliable than the modified sector method. For example, consider the case where a critical structure is changed inside the machine or some beam characteristics have been changed. While the sector method would require an additional set of measurements, Monte Carlo would only need simulation of the new structure. Deterministic computation methods for radiation transport, such as discrete ordinates is another approach that could be applied in the future but to my knowledge no work has been performed in this area.
REFRENCE

1. Khan, M. F. *Physics of Radiation Therapy*, 1st ed. (Lippincott Williams & Wilkins, 1984, USA)


APPENDIX A

21EX (S/N 1251) MEASUREMENTS

21EX (S/N 1251) SSD\textsubscript{eff} Curves

Figure (A-1). 21EX (S/N 1251), SSD\textsubscript{eff} for 6 MeV

\[ y = -4.3333 \times 10^{-2}x^4 + 1.2983 \times 10^0x^3 - 1.4128 \times 10^1x^2 + 6.7822 \times 10^1x - 3.5837 \times 10^1 \]

\[ R^2 = 9.9236 \times 10^{-1} \]

Figure (A-2). 21EX (S/N 1251), SSD\textsubscript{eff} for 9 MeV

\[ y = 2.8729 \times 10^{-3}x^5 - 1.3493 \times 10^{-1}x^4 + 2.3480 \times 10^0x^3 - 1.9105 \times 10^1x^2 + 7.4739 \times 10^1x - 2.7429 \times 10^1 \]

\[ R^2 = 9.9216 \times 10^{-1} \]

Figure (A-3). 21EX (S/N 1251), SSD\textsubscript{eff} for 12 MeV

\[ y = 9.9989 \times 10^{-3}x^5 - 3.3619 \times 10^{-1}x^4 + 4.2988 \times 10^0x^3 - 2.6036 \times 10^1x^2 + 7.6445 \times 10^1x - 4.2256 \times 10^0 \]

\[ R^2 = 9.8873 \times 10^{-1} \]
21EX (S/N 1251) SSD\(_{\text{eff}}\) Curves (cont.)

Figure (A-4). 21EX(S/N 1251), SSD\(_{\text{eff}}\) for 16 MeV

\[ y = -1.6188 \times 10^{-3}x^6 + 6.6163 \times 10^{-2}x^5 - 1.0847 \times 10^0x^4 + 9.0620 \times 10^0x^3 - 4.0272 \times 10^1x^2 + 
9.1023 \times 10^1x + 1.7638 \times 10^0 \]

\[ R^2 = 9.6982 \times 10^{-1} \]

Figure (A-5). 21EX(S/N 1251), SSD\(_{\text{eff}}\) for 20 MeV

\[ y = -1.5934 \times 10^{-3}x^6 + 6.2759 \times 10^{-2}x^5 - 9.8909 \times 10^{-1}x^4 + 7.9108 \times 10^0x^3 - 3.3467 \times 10^1x^2 + 
7.2332 \times 10^1x + 1.6555 \times 10^1 \]

\[ R^2 = 9.4943 \times 10^{-1} \]
21EX (S/N 1251), 6MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

**Figure (A-6). 21EX(S/N 1251); 6MeV; Insert Factor for 6×6 cm² cone**

\[ y = 9.9942E-02x^3 - 6.6410E-01x^2 + 1.5148E+00x - 1.9475E-01 \]

\[ R^2 = 1.0000E+00 \]

**Figure (A-7). 21EX(S/N 1251); 6MeV; Insert Factor for 10×10 cm² cone**

\[ y = 3.1267E-03x^5 - 5.3243E-02x^4 + 3.6084E-01x^3 - 1.2260E+00x^2 + 2.1035E+00x - 4.6740E-01 \]

\[ R^2 = 9.9968E-01 \]

**Figure (A-8). 21EX(S/N 1251); 6MeV; Insert Factor for 15×15 cm² cone**

\[ y = 7.4430E-04x^5 - 1.6546E-02x^4 + 1.4591E-01x^3 - 6.3786E-01x^2 + 1.3778E+00x - 1.5961E-01 \]

\[ R^2 = 9.9951E-01 \]
21EX (S/N 1251), 6MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (A-9). 21EX(S/N 1251); 6MeV; Insert Factor for 20×20 cm² cone

\[ y = 5.7843 \times 10^{-5} x^5 - 2.0424 \times 10^{-3} x^4 + 2.7601 \times 10^{-2} x^3 - 1.7735 \times 10^{-1} x^2 + 5.3637 \times 10^{-1} x + 4.0511 \times 10^{-1} \]

\[ R^2 = 9.9018 \times 10^{-1} \]

Figure (A-10). 21EX(S/N 1251); 6MeV; Insert Factor for 25×25 cm² cone

\[ y = -1.3418 \times 10^{-5} x^6 + 6.1667 \times 10^{-4} x^5 - 1.1185 \times 10^{-2} x^4 + 1.0202 \times 10^{-1} x^3 - 4.9164 \times 10^{-1} x^2 + 1.1840 \times 10 \]

\[ R^2 = 9.9018 \times 10^{-1} \]
21EX (S/N 1251), 9MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (A-11). 21EX(S/N 1251); 9MeV; Insert Factor for 6×6 cm² cone
\[ y = 4.1967E-02x^3 - 3.7588E-01x^2 + 1.1231E+00x - 1.2240E-01 \]
\[ R^2 = 9.9962E-01 \]

Figure (A-12). 21EX(S/N 1251); 9MeV; Insert Factor for 10×10 cm² cone
\[ y = -6.3477E-03x^4 + 9.6079E-02x^3 - 5.4011E-01x^2 + 1.3390E+00x - 2.3543E-01 \]
\[ R^2 = 9.9896E-01 \]

Figure (A-13). 21EX(S/N 1251); 9MeV; Insert Factor for 15×15 cm² cone
\[ y = -3.3674E-03x^4 + 5.9764E-02x^3 - 3.8952E-01x^2 + 1.1018E+00x - 1.3053E-01 \]
\[ R^2 = 9.9973E-01 \]
21EX (S/N 1251), 9MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (A-14). 21EX(S/N 1251); 9MeV; Insert Factor for 20×20 cm² cone

\[ y = 3.8068E-05x^5 - 1.6533E-03x^4 + 2.5690E-02x^3 - 1.8287E-01x^2 + 6.0056E-01x + 2.8104E-01 \]

\[ R^2 = 9.9137E-01 \]

Figure (A-15). 21EX(S/N 1251); 9MeV; Insert Factor for 25×25 cm² cone

\[ y = -2.4297E-05x^6 + 9.7741E-04x^5 - 1.5838E-02x^4 + 1.3210E-01x^3 - 5.9757E-01x^2 + 1.3889E+00x - 2.8795E-01 \]

\[ R^2 = 9.9871E-01 \]
2000CR (S/N 951), 12 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B- 16). 2000CR (S/N 951); 12 MeV, Insert Factors for 6×6 cm² cone

![Graph](image1)

\[ y = 5.8328 \times 10^{-2}x^3 - 4.8973 \times 10^{-1}x^2 + 1.3770 \times 10^1x - 3.1035 \times 10^{-1} \]

\[ R^2 = 9.9881 \times 10^{-1} \]

Figure (B- 17). 2000CR (S/N 951); 12 MeV, Insert Factors for 10×10 cm² cone

![Graph](image2)

\[ y = -3.5320 \times 10^{-3}x^4 + 5.7817 \times 10^{-2}x^3 - 3.5435 \times 10^{-1}x^2 + 9.6441 \times 10^{-1}x + 1.6791 \times 10^{-2} \]

\[ R^2 = 9.9929 \times 10^{-1} \]

Figure (B- 18). 2000CR (S/N 951); 12 MeV, Insert Factors for 15×15 cm² cone

![Graph](image3)

\[ y = 1.1746 \times 10^{-3}x^5 - 2.4295 \times 10^{-2}x^4 + 1.9961 \times 10^{-1}x^3 - 8.2281 \times 10^{-1}x^2 + 1.7216 \times 10^1x - 4.6701 \times 10^{-1} \]

\[ R^2 = 9.9978 \times 10^{-1} \]
2000CR (S/N 951), 12 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

**Figure (B-19).** 2000CR (S/N 951); 12 MeV, Insert Factors for 20×20 cm\(^2\) cone

\[ y = -5.8604 \times 10^{-4} x^4 + 1.4591 \times 10^{-2} x^3 - 1.3182 \times 10^{-1} x^2 + 5.0897 \times 10^{-1} x + 3.0642 \times 10^{-1} \]

\[ R^2 = 9.9190 \times 10^{-1} \]

**Figure (B-20).** 2000CR (S/N 951); 12 MeV, Insert Factors for 25×25 cm\(^2\) cone

\[ y = -2.6119 \times 10^{-5} x^6 + 1.0270 \times 10^{-3} x^5 - 1.6247 \times 10^{-2} x^4 + 1.3250 \times 10^{-1} x^3 - 5.8954 \times 10^{-1} x^2 + 1.3658 \times 10^0 x - 2.8372 \times 10^{-1} \]

\[ R^2 = 9.9942 \times 10^{-1} \]
2000CR (S/N 951), 16 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B-21). 2000CR (S/N 951); 16 MeV, Insert Factors for 6×6 cm² cone

Figure (B-22). 2000CR (S/N 951); 16 MeV, Insert Factors for 10×10 cm² cone

Figure (B-23). 2000CR (S/N 951); 16 MeV, Insert Factors for 15×15 cm² cone
2000CR (S/N 951), 16 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (B-24). 2000CR (S/N 951); 16 MeV, Insert Factors for 20×20 cm$^2$ cone

Figure (B-25). 2000CR (S/N 951); 16 MeV, Insert Factors for 25×25 cm$^2$ cone
21EX (S/N 1251), 20 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (A-26). 21EX(S/N 1251); 20 MeV; Insert Factor for 6×6 cm$^2$ cone

Figure (A-27). 21EX(S/N 1251); 20 MeV; Insert Factor for 10×10 cm$^2$ cone

Figure (A-28). 21EX(S/N 1251); 20 MeV; Insert Factor for 15×15 cm$^2$ cone
21EX (S/N 1251), 20 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (A-29). 21EX (S/N 1251); 20 MeV; Insert Factor for 20×20 cm² cone

\[y = 3.0592\times10^{-5}x^5 - 8.2539\times10^{-4}x^4 + 8.6434\times10^{-3}x^3 - 4.5430\times10^{-2}x^2 + 1.2274\times10^{-1}x + 8.9142\]
\[R^2 = 0.9847\]

Figure (A-30). 21EX (S/N 1251); 20 MeV; Insert Factor for 15×15 cm² cone

\[y = -7.8486\times10^{-5}x^4 + 2.2317\times10^{-3}x^3 - 2.2831\times10^{-2}x^2 + 9.6390\times10^{-2}x + 8.8916\]
\[R^2 = 0.9415\]
APPENDIX B

2000CR (S/N 951) MEASUREMENTS

2000CR (S/N 951) SSD_{eff} Curves

Figure (B-1). 2000CR (S/N 951), SSD_{eff} for 6 MeV

\[ y = -2.8929 \times 10^{-2}x^4 + 9.3768 \times 10^{-1}x^3 - 1.1217 \times 10^1x^2 + 5.9707 \times 10^1x - 3.0134 \times 10^1 \]

\[ R^2 = 0.99124 \]

Figure (B-2). 2000CR (S/N 951), SSD_{eff} for 9 MeV

\[ y = 9.2784 \times 10^{-3}x^5 - 3.2040 \times 10^{-1}x^4 + 4.2522 \times 10^0x^3 - 2.7225 \times 10^1x^2 + 8.6774 \times 10^1x - 2.8615 \times 10^1 \]

\[ R^2 = 0.99195 \]

Figure (B-3). 2000CR (S/N 951), SSD_{eff} for 12 MeV

\[ y = 1.2523 \times 10^{-2}x^3 - 4.1024 \times 10^{-1}x^4 + 5.0890 \times 10^0x^3 - 2.9772 \times 10^1x^2 + 8.4059 \times 10^1x - 9.9054 \times 10^0 \]

\[ R^2 = 0.98888 \]
2000CR (S/N 951) SSD\textsubscript{eff} Curves (cont.)

Figure (B-4). 2000CR (S/N 951), SSD\textsubscript{eff} for 16 MeV

\[y = -0.0006x^6 + 0.0325x^5 - 0.654x^4 + 6.3876x^3 - 31.945x^2 + 79.389x + 5.4663\]

\[R^2 = 0.9752\]

Figure (B-5). 2000CR (S/N 951), SSD\textsubscript{eff} for 20 MeV

\[y = 8.7889E-03x^5 - 2.8826E-01x^4 + 3.5400E+00x^3 - 2.0060E+01x^2 + 5.3849E+01x + 2.5082E+01\]

\[R^2 = 9.4372E-01\]
2000CR (S/N 951); 6 MeV; Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B- 6). 2000CR (S/N 951); 6 MeV; Insert Factors for 6×6 cm$^2$ cone

\[ y = 4.2250 \times 10^{-2}x^3 - 3.7761 \times 10^{-1}x^2 + 1.1138 \times 10^0x - 8.2018 \times 10^{-2} \]
\[ R^2 = 9.9999 \times 10^{-1} \]

Figure (B- 7). 2000CR (S/N 951); 6 MeV; Insert Factors for 10×10 cm$^2$ cone

\[ y = 1.9468 \times 10^{-4}x^5 - 7.2905 \times 10^{-3}x^4 + 8.9680 \times 10^{-2}x^3 - 4.9380 \times 10^{-1}x^2 + 1.2541 \times 10^0x - 1.8252 \times 10^{-1} \]
\[ R^2 = 9.9924 \times 10^{-1} \]

Figure (B- 8). 2000CR (S/N 951); 6 MeV; Insert Factors for 15×15 cm$^2$ cone

\[ y = 3.3453 \times 10^{-4}x^5 - 1.0827 \times 10^{-2}x^4 + 1.1774 \times 10^{-1}x^3 - 5.8233 \times 10^{-1}x^2 + 1.3495 \times 10^0x - 1.8469 \times 10^{-1} \]
\[ R^2 = 9.9998 \times 10^{-1} \]
2000CR (S/N 951); 6 MeV; Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (B- 9). 2000CR (S/N 951); 6 MeV; Insert Factors for 20×20 cm² cone

\[ y = 5.0941 \times 10^{-5}x^5 - 1.9337 \times 10^{-3}x^4 + 2.7639 \times 10^{-2}x^3 - 1.8566 \times 10^{-1}x^2 + 5.8215 \times 10^{-1}x + 3.2579 \times 10^{-1} \]

\[ R^2 = 9.8308 \times 10^{-1} \]

Figure (B- 10). 2000CR (S/N 951); 6 MeV; Insert Factors for 25×25 cm² cone

\[ y = -2.4475 \times 10^{-5}x^6 + 9.9023 \times 10^{-4}x^5 - 1.6092 \times 10^{-2}x^4 + 1.3407 \times 10^{-1}x^3 - 6.0240 \times 10^{-1}x^2 + 1.3799 \times 10^1x - 2.4955 \times 10^{-1} \]

\[ R^2 = 9.9664 \times 10^{-1} \]
2000CR (S/N 951), 9 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B-11). 2000CR (S/N 951); 9 MeV, Insert Factors for 6×6 cm² cone

\[ y = 5.3847 \times 10^{-2}x^3 - 4.6044 \times 10^{-1}x^2 + 1.3168 \times 10^0x - 2.6874 \times 10^{-1} \]
\[ R^2 = 9.9884 \times 10^{-1} \]

Figure (B-12). 2000CR (S/N 951), 9 MeV, Insert Factors for 10×10 cm² cone

\[ y = 1.6290 \times 10^{-4}x^5 - 5.3798 \times 10^{-3}x^4 + 6.5390 \times 10^{-2}x^3 - 3.7078 \times 10^{-1}x^2 + 9.8934 \times 10^{-1}x + 2.4498 \times 10^{-3} \]
\[ R^2 = 9.9993 \times 10^{-1} \]

Figure (B-13). 2000CR (S/N 951); 9 MeV, Insert Factors for 15×15 cm² cone

\[ y = 6.7897 \times 10^{-4}x^5 - 1.5447 \times 10^{-2}x^3 + 1.4074 \times 10^{-1}x^2 + 6.4302 \times 10^{-2}x^1 + 1.4705 \times 10^0x - 3.3029 \times 10^{-1} \]
\[ R^2 = 9.9982 \times 10^{-1} \]
2000CR (S/N 951), 9 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (B- 14). 2000CR (S/N 951); 9 MeV, Insert Factors for $20 \times 20$ cm$^2$ cone

\[ y = 6.4691E-05x^5 - 2.2997E-03x^4 + 3.1552E-02x^3 - 2.0764E-01x^2 + 6.4966E-01x + 2.3927E-01 \]

\[ R^2 = 9.9474E-01 \]

Figure (B- 15). 2000CR (S/N 951); 9 MeV, Insert Factors for $25 \times 25$ cm$^2$ cone

\[ y = -2.6620E-05x^6 + 1.0555E-03x^5 - 1.6845E-02x^4 + 1.3838E-01x^3 - 6.1710E-01x^2 + 1.4173E+00x - 3.0032E-01 \]

\[ R^2 = 9.9929E-01 \]
2000CR (S/N 951), 12 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B-16). 2000CR (S/N 951); 12 MeV, Insert Factors for 6×6 cm$^2$ cone

\[ y = 5.8328E-02x^3 - 4.8973E-01x^2 + 1.3770E+00x - 3.1035E-01 \]
\[ R^2 = 9.9881E-01 \]

Figure (B-17). 2000CR (S/N 951); 12 MeV, Insert Factors for 10×10 cm$^2$ cone

\[ y = -3.5320E-03x^4 + 5.7817E-02x^3 - 3.5435E-01x^2 + 9.6441E-01x + 1.6791E-02 \]
\[ R^2 = 9.9929E-01 \]

Figure (B-18). 2000CR (S/N 951); 12 MeV, Insert Factors for 15×15 cm$^2$ cone

\[ y = 1.1746E-03x^5 - 2.4295E-02x^4 + 1.9961E-01x^3 - 8.2281E-01x^2 + 1.7216E+00x - 4.6701E-01 \]
\[ R^2 = 9.9978E-01 \]
2000CR (S/N 951), 12 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

**Figure (B-19).** 2000CR (S/N 951); 12 MeV, Insert Factors for 20×20 cm² cone

\[ y = -5.8604\times10^{-4}x^4 + 1.4591\times10^{-2}x^3 - 1.3182\times10^{-1}x^2 + 5.0897\times10^{-1}x + 3.0642\times10^{-1} \]

\[ R^2 = 9.9190\times10^{-1} \]

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**Figure (B-20).** 2000CR (S/N 951); 12 MeV, Insert Factors for 25×25 cm² cone

\[ y = -2.6119\times10^{-5}x^6 + 1.0270\times10^{-3}x^5 - 1.6247\times10^{-2}x^4 + 1.3250\times10^{-1}x^3 - 5.8954\times10^{-1}x^2 + 1.3658\times10^{-2}x - 2.8372\times10^{-3} \]

\[ R^2 = 9.9942\times10^{-1} \]

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</table>
2000CR (S/N 951), 16 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B-21). 2000CR (S/N 951); 16 MeV, Insert Factors for 6×6 cm$^2$ cone

\[ y = 4.7540E-02x^3 - 4.0240E-01x^2 + 1.1366E+00x - 7.9268E-02 \]

\[ R^2 = 9.9892E-01 \]

Figure (B-22). 2000CR (S/N 951); 16 MeV, Insert Factors for 10×10 cm$^2$ cone

\[ y = -7.3649E-03x^4 + 1.0583E-01x^3 - 5.6285E-01x^2 + 1.3247E+00x - 1.7898E-01 \]

\[ R^2 = 9.9816E-01 \]

Figure (B-23). 2000CR (S/N 951); 16 MeV, Insert Factors for 15×15 cm$^2$ cone

\[ y = 1.0001E-03x^5 - 2.0750E-02x^4 + 1.7058E-01x^3 - 7.0082E-01x^2 + 1.4563E+00x - 2.2850E-01 \]

\[ R^2 = 9.9985E-01 \]
2000CR (S/N 951), 16 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (B-24). 2000CR (S/N 951); 16 MeV, Insert Factors for 20×20 cm² cone

\[ y = 7.6886E-05x^5 - 2.4237E-03x^4 + 3.0066E-02x^3 - 1.8419E-01x^2 + 5.5746E-01x + 3.5734E-01 \]

\[ R^2 = 9.9500E-01 \]

Figure (B-25). 2000CR (S/N 951); 16 MeV, Insert Factors for 25×25 cm² cone

\[ y = -2.8284E-05x^6 + 1.0985E-03x^5 - 1.7092E-02x^4 + 1.3633E-01x^3 - 5.8960E-01x^2 + 1.3208E+00x - 1.9348E-01 \]

\[ R^2 = 9.9928E-01 \]

2000CR (S/N 951), 20 MeV, Insert Factors Curves
(The equations represent the insert factors at gap = 0)

Figure (B-26). 2000CR (S/N 951); 20 MeV, Insert Factors for 6×6 cm² cone

Figure (B-27). 2000CR (S/N 951); 20 MeV, Insert Factors for 10×10 cm² cone

Figure (B-28). 2000CR (S/N 951); 20 MeV, Insert Factors for 15×15 cm² cone
2000CR (S/N 951), 20 MeV, Insert Factors Curves (cont.)
(The equations represent the insert factors at gap = 0)

Figure (B-29). 2000CR (S/N 951); 20 MeV, Insert Factors for 20\times20 cm^2 cone

\[ y = 2.7671\times10^{-5}x^5 - 7.5391\times10^{-4}x^4 + 8.0287\times10^{-3}x^3 - 4.3301\times10^{-2}x^2 + 1.2110\times10^{-1}x + 8.8651\times10^{-1} \]
\[ R^2 = 9.8430\times10^{-1} \]

Figure (B-30). 2000CR (S/N 951); 20 MeV, Insert Factors for 25\times25 cm^2 cone

\[ y = -1.0825\times10^{-5}x^6 + 4.0438\times10^{-4}x^5 - 5.9641\times10^{-3}x^4 + 4.4260\times10^{-2}x^3 - 1.7481\times10^{-1}x^2 + 3.5296\times10^{-1}x + 7.3882\times10^{-1} \]
\[ R^2 = 9.9549\times10^{-1} \]
## APPENDIX C

### MUCALC PROGRAM CALCULATION EXAMPLE

#### Monitor Unit Calculation

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<th>Treatment Machine</th>
<th>Calculation Site</th>
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<tr>
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<td>Another Physicist</td>
<td>Varian 21EX 18e</td>
<td>Calculation Site Depth (cm) 1.3</td>
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<td>Chad Durn</td>
<td>Sheldon Johnson</td>
<td>Hammond 2000R 12e</td>
<td>Effective Depth (cm) 1.3</td>
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<td>Kenneth Lo, MD</td>
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#### Electron Blocking Factor Calculation

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| Averages         | 0.9496874 | 48.87716 | 0.7823789 |

<p>| Percent difference | - 0.4% |</p>
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<th>Area [cm²]</th>
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<th>Visible Source Distance</th>
<th>Current Structure</th>
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APPENDIX D

ERROR ANALYSIS DERIVATION

Let us consider TPC₁, TPC₂. In the formulation below T corresponds to the TPC and M refers to the electrometer reading.

\[ \Delta T_1 = T_1 - T_0 \quad \text{and} \quad \Delta T_2 = T_2 - T \]

\[ R(T_1, T_2) = \frac{M_2(T_2)}{M_1(T_1)} \]

\[ \Delta R = \frac{\partial R}{\partial T_1} \Delta T_1 + \frac{\partial R}{\partial T_2} \Delta T_2 \]

\[ \text{Var}(R) = E(R - R_o)^2 = E[\Delta R^2] \]

\[ = E \left[ \frac{\partial R}{\partial T_1} \Delta T_1 + \frac{\partial R}{\partial T_2} \Delta T_2 \right]^2 = E \left[ \left( \frac{\partial R}{\partial T_1} \right)^2 \Delta T_1^2 + 2 \frac{\partial R}{\partial T_1} \frac{\partial R}{\partial T_2} \Delta T_1 \Delta T_2 + \left( \frac{\partial R}{\partial T_2} \right)^2 \Delta T_2^2 \right] \]

\[ = \left( \frac{\partial R}{\partial T_1} \right)^2 E[\Delta T_1^2] + \left( \frac{\partial R}{\partial T_2} \right)^2 E[\Delta T_2^2] + 2 \left( \frac{\partial R}{\partial T_1} \right) \left( \frac{\partial R}{\partial T_2} \right) E[\Delta T_1 \Delta T_2] \]

\[ \text{Var}\Delta T_1 = E[\Delta T_1^2] \]

\[ \text{Var}\Delta T_2 = E[\Delta T_2^2] \]

\[ \text{Cov}(\Delta T_1, \Delta T_2) = E[\Delta T_1 \Delta T_2] = 0 \]

\( \Delta T_1 \Delta T_2 \) are assumed uncorrelated since the temperature and pressure measurements on one day do not affect those performed on other days.

\[ \sigma_k^2 = \left( \frac{\partial R}{\partial T_1} \right)^2 \text{Var}(T_1) + \left( \frac{\partial R}{\partial T_2} \right)^2 \text{Var}(T_2) \]

\[ \frac{\partial R}{\partial T_1} = M_2 \left( \frac{\partial}{\partial T_1} \left[ \frac{1}{M_1(T_1)} \right] \right) = M_2 \left( - \frac{1}{M_1} \right) = - \frac{M_2}{M_1} \]
\[
\frac{\partial R}{\partial T_2} = \left( \frac{\partial M_2(T_2)}{\partial T_2} \right) \left[ \frac{1}{M_1} \right] = \frac{M_2}{M_1}
\]

\[
\sigma_r^2 = \left( \frac{M_2}{M_1} \right)^2 [\text{Var}(T_1) + \text{Var}(T_2)]
\]

To find \(\text{Var}(T_1)\):

\[
TPC = \frac{273.15 + T(\degree C)}{295.15} \times \frac{760}{P(\text{mmHg})}
\]

from error analysis, if

\[
Z = X^n Y^n
\]

then

\[
\frac{\sigma_z^2}{Z^2} = \left( \frac{m\sigma_X}{X^n} \right)^2 + \left( \frac{n\sigma_Y}{Y^n} \right)^2
\]

so we get the variance in the TPC

\[
\sigma_{TPC} = TPC \times \sqrt{\frac{760}{295.15} \sqrt{\left( \frac{0.4}{T + 273.15} \right)^2 + \left( \frac{0.001}{P} \right)^2}} \approx TPC \times \frac{0.64}{T + 273.15}
\]

similarly for \(\sqrt{R} = \sqrt{\frac{M_2(T_2)}{M_1(T_1)}}\), then

\[
\sigma_{\sqrt{R}}^2 = \frac{1}{4} \left( \frac{M_2}{M_1} \right)^2 [\text{Var}(T_1) + \text{Var}(T_2)]
\]
21EX (S/N) 1251; 6 MeV; Insert factors for 25×25 cone inserts
The SSD\textsubscript{eff} values for 21EX (S/N) 1251 for 12 MeV
Ahmet Bulut was born in Burgwedel, Germany, on April 2, 1974, to Dr. Khayruddin Bulut and Mrs. Sarah Kurugi. The first capitol in Islam, Al-Madinah Al-Munawwarah, Saudi Arabia, was the city where he grew up and finished high school. On 1992, he was accepted in the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Immediately after completing the bachelor degree requirements in physics, he began his graduate studies in general physics. However, to seek international experience, Ahmet pursued graduate studies in medical physics abroad. After a brief stay in University of Alberta, Edmonton, Alberta, he joined the Physics and Astronomy Department at the Louisiana State University in August 1999 in pursuit of a master degree in Medical and Health Physics. After finishing the course work, he began his residency in Mary Perkins Cancer Center, Baton Rouge, Louisiana. While finishing the master degree at the Louisiana State University, he joined the Department of Radiology at the University of Texas Health Science Center at San Antonio, San Antonio, Texas, in pursuit of a doctoral degree in medical physics. Ahmet is also a member of the American Association of Physicists in Medicine (AAPM).