Validation of a Monte Carlo based Treatment Planning System (TPS) for electron beams

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December, 2006

A thesis submitted to the Faculty of Graduate Studies and Research of McGill University in partial fulfillment of the requirements of the degree of Master of Science in Medical Radiation Physics

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DEDICATION

To my home, wherever it is.
ACKNOWLEDGMENTS

First, I would like to thank to William Parker and Dr. Slobodan Devic. I truly do appreciate all the help, support, and guidance that I received from them throughout this project. They were always there for me and never hesitated to answer my questions and address my problems.

Many thanks also to Dr. Ervin Podgorsak for the wonderful program he has created here at McGill over the 25 years of his directorship in this department.

This project would not have been possible without the help of the Michael Evans and Dr. Jan Seuntjens, I would like to express my sincere thanks to them. I would like to acknowledge all the assistance that I received from Dr. Wamied Abdel-Rahman, as well.

I would like to express my gratitude to Margery Knewstubb, the department secretary, as well as all the staff, professors, and clinical physicists for their help, support, and smiles.

My sincere thanks to all my colleagues and fellow students, both at the masters and the PhD level, for their support. I know that it would have been much more difficult to continue the program without their academic-related as well as moral support.

And most importantly, I thank the Lord Almighty, the One who created all things and who has a reason behind them also.
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ABSTRACT

A commercial electron dose calculation software (Eclipse™) implementation based on the Macro Monte Carlo algorithm has been introduced. Eclipse™ initial configurations were performed for all available electron beam energies 6, 9, 12, 16, and 20 MeV. We evaluated the electron Monte Carlo (eMC) module of the Eclipse™ using a verification data set comprised of depth dose curves, profiles, Relative Output Factors (ROF), and 2-D dose distributions in the transverse plane in a homogeneous phantom. The verification data set was comprised of measurements performed for combinations of 6, 9, 12, 16, and 20 MeV beam energies with five standard field sizes and thirteen irregularly shaped fields under three phantom setups. The phantom setups were normal beam incidence at source-to-surface distance (SSD) = 100cm, normal incidence with extended SSD=110cm, and oblique incidence with extended SSD=110cm. Calculations were performed in a digital phantom with the maximum number of particles accepted by Eclipse™ with a grid spacing that was no larger than approximately one-tenth the distal falloff distance of the electron depth dose curve from 80% to 20% of the maximum dose. Overall, the agreement between the calculated dose distributions and measured ones was good for fields larger than 2 cm to better than 3% dose difference and 3 mm distance-to-agreement.
ABRÉGÉ

Le logiciel commercial de calcul de dose électron (Eclipse™) basé sur l'algorithme Monte Carlo MACRO a été introduit. Les configurations initiales d'Eclipse ont été réalisées pour des faisceaux d'électron d'énergies 6, 9, 12, 16 et 20 MeV. Nous avons évalué le module électron Monte Carlo (eMC) d'Eclipse en utilisant un ensemble de données de vérification telles que les courbes de rendement en profondeur, les profils, les "Relative Output Factors" (ROF), et des distributions de dose 2-D dans le plan transverse d'un fantôme homogène. Cet ensemble de données de vérification correspondaient à des mesures effectuées pour des combinaisons de faisceaux d'énergies 6, 9, 12, 16 et 20 MeV avec cinq tailles de champs standard et treize formes de champs irrégulières sous trois positions différentes du fantôme. Le fantôme a été positionné perpendiculairement au faisceau incident à une distance source-surface du fantôme (DSP) = 100 cm, puis de nouveau perpendiculairement au faisceau incident à une DSP = 110 cm, et enfin avec une incidence oblique à une DSP étendue de 110 cm. Les calculs ont été réalisés dans un fantôme numérique avec le nombre maximum de particules accepté par Eclipse™ et avec une dimension de l'espace des phases pas plus importante qu'un dixième de la distance latérale de la courbe de rendement en profondeur des électrons séparant le 80 % et le 20 % de la dose maximum. Dans l'ensemble, l'accord entre les distributions de dose calculées et celles mesurées était satisfaisant pour des champs plus grands que 2 cm avec au mieux 3 % de différence de dose et 3 mm de décalage.
Chapter 1: Introduction

1.1 Cancer Treatment with radiation

Among 12 causes of premature death in Canada in 2002 as represented by Potential Years Life Lost (PYLL), cancer was the leading cause for men and women: 990 000 potential years were lost as a result of cancer representing 32% of the PYLL resulting from all causes of death. Diseases of the heart were the second leading cause [1].

Approximately 60% of patients diagnosed with cancer are treated with radiation; half of those are considered curable because their tumours are localized and sensitive to radiation. Radiation has been used to treat cancer for almost 100 years. Radiation therapy is the use of high energy, penetrating radiation to destroy cancer cells. The primary purpose of radiation therapy is to eliminate or shrink localized cancers, while sparing as much healthy tissues as possible [2]. Successful therapy depends on choosing the right type of radiation and applying the right amounts to the right places.

Over last 30 years Radiation therapy has progressed from the use of orthovoltage x-rays and Cobalt units to treatments with high energy-photon and electron beams with a wide support of treatment planning systems [3].

1.2 Electron beams in Radiation therapy

About 10% of cancer patients receive electron therapy. Electron beams are useful for shallow cancers due to the electrons limited penetrating power, which spares deeper lying tissues.
The most attractive characteristic of the electrons in radiation therapy is the shape of depth dose (PDD) curve [3]. An example of a photon and electron beam PDD is shown on the Figure 1.1

\[ \text{Photons and Electrons PDD curves} \]

![Photons and Electrons PDD curves](image)

**Figure 1.1:** Example of photon and electron PDD curves. (---) - Solid line 10 MV photon beam curve, (-0-) - 9 MeV electron beam curve.

The electron PDD curve displays four distinguishable differences from megavoltage photon depth dose curves:

- Higher skin/or entrance/ dose;
- Moderately flat plateau at depth of maximum dose \( (d_{\text{max}}) \);
- Steep fall-off after \( d_{\text{max}} \);
- Bremsstrahlung tail produced by x-rays generated in scattering foil, the collimating system and the irradiated medium;

The advantages to be drawn from this type of depth dose curve are greatest at energies up to 20 MeV allowing us to use the electron beams for irradiation of sub-dermal tumors with the benefit of sparing underlying healthy tissues. This fact makes electrons ideal for the irradiation of all skin and lip cancers and residual tumors, as well as superficial lymph nodes.
1.3 Algorithms and Treatment Planning Systems (TPS) for electrons

Prior to the delivery of radiation treatment, a treatment plan needs to be developed. The objective of treatment planning is to determine adequate treatment techniques and arrangements of the radiation beams with the goal of obtaining regions of high and uniform dose which conform to the shape of the tumor while minimizing damage to healthy organs. One of important steps in radiation treatment planning process is to determine dose distribution in the body because in general, is not possible to measure dose inside the patient non-invasively [4].

In order to perform radiation dose distribution calculations in phantom or in the human body, calculation algorithms are required to model successfully the beam behavior during its transition through matter. The fundamental requirement for the model is that it should be capable of reproducing the dose distributions obtained experimentally [3].

Presently, due to limitations in electron beam algorithms, and the generally simplistic applications of electrons in clinical use, the implementation of TPS for electron beam patients has been minimal. The standard in fact, is to plan the patient clinically at the treatment unit, and estimate the dose distribution from tabulated data.

The functionality and quality of any Treatment Planning System (TPS) is dependent on the type of algorithms used in the different steps of the planning process. An algorithm is defined as sequence of instructions that operates on a set of input data, transforming that information into a set of output results that are of interest to the user [5]. The most basic algorithm for dose calculations generates the dose at any point within the patient while taking into account the patient and beam characteristics.
The approach currently used in most treatment planning systems to model the Linac as a radiation source based on measurements taken during the commissioning stage. Actual radiation dose calculation in most sophisticated Treatment Planning Systems (TPS) is done in patient voxel geometry by using a pencil beam or convolution model.[6] [7].

1.3.1 Electron 3D Pencil Beam Algorithm

The electron pencil beam algorithm as developed by Hogstrom in 1981 [8] is used to predict electron dose distributions in the presence of inhomogeneous media for use in radiation treatment planning. An electron beam is modeled as a collection of forward-directed "pencils" at the final plane of collimation at the Source-to-Cone Distance (SCD). The electron pencil beams at subsequent planes are redistributed in a Gaussian distribution due to both scatter occurring above the SCD (in air scatter) and scatter in the medium due to Multiple Coulomb Scattering (MCS).

The lateral spread of electrons occurring below the SCD due to scattering occurring in air is determined based on the change in the lateral spread of the penumbra of air profiles. The lateral spread of electrons as they traverse inhomogeneous media is determined according to the Fermi-Eyges theory of thick-target Multiple Coulomb Scattering (MCS). The air and MCS Gaussian scatter distributions serve as kernels with which the pencils are convolved.

The first step in the calculation is to convolve the initial pencil beam intensity distribution as projected at a given depth with the air Gaussian at that depth. The next step is to determine the central-axis term using measured percent depth dose (PDD) data. A photon component is removed from the measured PDDs to separate the electron and photon components of the beam. The central-axis term is then determined as the dose deposited at depth by a pure electron pencil
beam. Each point in the air-convolved distribution is multiplied by the central-axis term for the point's corresponding effective depth. Each point is also multiplied by an inverse square factor accounting for intensity variations between the distance between the source and the calculation point.

The next step in 3D Pencil beam electron algorithm is to convolve the points with the position-dependent MCS Gaussian. The lateral distribution of photons is determined by multiplying the photon component of the PDD data by a penumbra term dependent on the lateral spread of the air Gaussian. Finally, the electron and photon distributions are added back together in order to obtain the final dose distribution.

The most well-known shortcoming of the pencil beam algorithm is its inability to accurately model the effects of tissue density heterogeneities. [9]

1.3.2 Electron Monte Carlo Algorithm

The Monte Carlo method is currently the most accurate algorithm for dose calculation for electron beams and can significantly reduce uncertainties in dose calculation [10] [11] [12]. In order to achieve this accuracy, detailed information is required about the beam. This includes the energy, angular and spatial distributions of the particles in the clinical beam. One approach to determine the electron beam characteristics is to simulate the transport of the particles through the treatment head and phantom (or patient) geometry using the Monte Carlo technique.

Monte Carlo simulations of the accelerator head are done in which a record is kept of the particle initial phase-space, including the charge, energy, direction and position of every particle that emerges from the treatment head, along with a tag regarding the details of the particle history such as where the particle has
interacted, where it is created if it is secondary particle, whether there is a Bremsstrahlung photon involved in particle history, etc [13]. Various beam models are designed from a single point source to a sophisticated multiple-source models which treat particles from different parts of the linear accelerator as they emerge from different sub-sources. In this study, a commercial treatment planning system (TPS) Eclipse™ (Varian Medical Systems, Inc. (VMS, Las Vegas, NV) is under investigation. Eclipse™ uses an eMC algorithm for dose distribution calculation from high-energy electrons. The Initial Phase Space (IPS) model used in Eclipse™ is a multiple-source type model, adapted from the Rotterdam IPS model [14]. This is a fast implementation of the Monte Carlo method. A detailed overview of the Electron Monte Carlo (eMC) Algorithm is made in Chapter 3 of this work.

1.4 Commissioning of the Treatment Planning System (TPS)

The process of radiation therapy is complex and involves a series of steps beginning with patient diagnosis and terminating with the treatment of a specified target volume with the prescribed dose delivered with specific energy modalities and beam parameters. The accuracy of each step involved in the process has a direct impact on the treatment outcome. One of the components in this process is computerized treatment planning dose calculations.

Most treatment planning Quality Assurance (QA) is primarily concerned with dose calculation verification. The QA process can be divided into the following 3 general categories [15]:

1. Acceptance testing
2. Commissioning
3. Reproducibility testing (routine QA)
Acceptance testing confirms that the TPS performs according to the manufacturer specifications. Commissioning determines the accuracy of the TPS under various performances conditions and includes all steps necessary to make TPS system clinical. Reproducibility testing ensures consistency of operation and performance of the results produced by the TPS.

The commissioning process as described in TG-53 [16] includes two distinct components: non-dosimetric testing and dosimetric testing. Non-dosimetric testing aspects are those not directly related to dose calculation; these include proper calibration and operation of peripheral devices (digitizers, film scanners, printers, etc.), proper handling of anatomical structures and reference definitions (regions of interest, 2D and 3D structures), proper transfer and calibration of data from networked imaging systems (CT, MRI), beam positioning and definition and hardcopy output format and accuracy.

The dosimetric testing for external beam treatment planning includes verification of the accuracy and self-consistency of the input dataset, proper format and accuracy of data input to the system, relative dose calculation verification (comparing measured and calculated dose distributions), absolute output and plan normalization, and finally clinical case test verification.

The criteria for acceptability of computer generated dose distribution values reflect the inaccuracies of both measured and calculated values. The major sources of uncertainties (excluding treatment planner input errors) include the measured data, data entry, data display and output, and algorithm [17]. This work will focus on the dosimetric tests required for the commissioning of the Eclipse™ TPS Monte Carlo module.
1.4.1 Commissioning and acceptability criteria

Certain objective goals must be set for the commissioning process. Although these objectives may vary from institution to institution, and in fact depend on the type of TPS and treatment delivery that is involved, the Van Dyk criteria [17] are generally considered as the benchmark. The Van Dyk suggested criteria of acceptability for electron beam dose calculations are summarized in Table 1.1.

1.5 Goals of the thesis

The main goal of this work is to describe and perform the commissioning process for a commercially available, Monte Carlo based, electron beam treatment planning system.

The work is divided into sections as follows: Collection of data required by the TPS, fine tuning of the calculation model, and verification of calculation model with respect to clinically relevant situations by performing a further set of measurements and comparing results with calculation.
### Criteria of acceptability for electron beam dose calculations

<table>
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<th>Criterion</th>
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<tbody>
<tr>
<td>A. Homogeneous calculation (no shields)</td>
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</tr>
<tr>
<td>1. Central ray data (except in build-up region)</td>
<td>2%</td>
</tr>
<tr>
<td>2. High dose region—low dose gradient</td>
<td>4%</td>
</tr>
<tr>
<td>3. Large dose gradients (&gt;30% per cm)</td>
<td>4 mm</td>
</tr>
<tr>
<td>4. Small dose gradients in low dose region</td>
<td></td>
</tr>
<tr>
<td>(i.e. &lt;7% of normalization dose)</td>
<td>4%</td>
</tr>
<tr>
<td>B. Inhomogeneity corrections</td>
<td></td>
</tr>
<tr>
<td>1. Central ray (slab geometry, in regions of electron equilibrium)</td>
<td>5%</td>
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<tr>
<td>C. Composite uncertainty, anthropomorphic phantom,</td>
<td></td>
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<tr>
<td>contour correction, inhomogeneities, shields, irregular</td>
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<tr>
<td>fields, off axis</td>
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<tr>
<td>1. High dose region—low dose gradient</td>
<td>7%</td>
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<td>2. Large dose gradient (&gt;30% per cm)</td>
<td>5 mm</td>
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<tr>
<td>3. Small dose gradients in low dose region</td>
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<tr>
<td>(i.e. &lt;7% of central ray dose)</td>
<td>5%</td>
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Table 1.1: Criteria of acceptability for electron beam dose calculations [17].
References:


Chapter 2: Electron beam physics

In this chapter we will discuss various processes involved in the interaction of photons and electrons as they move through the medium. “Stopping power” will be introduced as the quantity accepted in practice for quantifying electron energy losses along their tracks during passage through matter. Some clinical aspects of electron beams will be highlighted: electron depth dose curves, dose profiles and output factors. Electron energy determination, the range concept of electron beams, and field shaping of electron beams will be introduced as well.

2.1 Electron interactions with matter

Electrons interact with matter through Coulomb force interactions with atomic orbital electrons and atomic nuclei. The energy losses usually take place in small increments and an electron must suffer many collisions before it loses all of its kinetic energy [1]. The type of interaction a passing electron undergoes is largely determined by its energy and the proximity to the nucleus with which it interacts. In general, there are two different energy loss processes: (1) collisional losses and (2) radiative losses. The probability of the type of energy loss interaction depends on the classical impact parameter $b$, (defined as the perpendicular distance between the electron direction before interaction and the atomic nucleus) and the classical atomic radius $a$, as can be seen in (Figure 2.1) [2].
2.1.1 Collisional losses

2.1.1.1 Soft Collisions (b >> a)

If the impact parameter b of the passing electron is large compared with the dimensions of the atom a, the atom interacts as a whole with the electron Coulomb force field. Such an interaction results in the excitation of the atom, where an electron from the inner shell is moved to an external orbit or in ionization of the atom by the ejection of a valence shell electron. The energy requirements for these two processes to occur are only in the order of few eV and therefore results in a negligible energy loss for the impinging electron. The excited atom dissipates the excess of the energy by emitting visible radiation or energy is imparted to the medium in the form of heat (phonons). Soft collisions are a frequent type of interaction, and account for about half of the energy transferred to the absorber.
2.1.1.2 Hard collisions or “knock-on” collisions (b~a)

When the distance of closest approach is of the order of the atomic radius, the traversing electron will interact directly with one of the atomic electrons. If the kinetic energy of the incoming electron is enough to overcome the binding energy of the orbital electron, the orbital electron is ejected from the shell and the atom becomes a positive ion. In general, if the removed electron kinetic energy is more than 100 eV, the ejected electron is called a “delta ray” and is capable of producing ionization and excitations of its own. Direct “knock-on” collisions with orbital electrons, resulting in large energy transfers are quite rare. Although the number of hard collisions is smaller compared to soft collisions, the net amount of energy deposition from these two processes is comparable. For energies of the order of a few MeV, soft and hard collisions are major types of energy degradation mechanisms experienced by electron beams.

2.1.2 Radiative losses (b<<a)

Radiative losses result from the electron passing in close proximity to the nucleus. If a collision results in the conversion of the energy lost by the electron into a photon, this is referred to as a radiative loss. The probability for such an interaction to happen is high if impact parameter of the electrons is smaller than the atomic radius. In this case, the passing electron under the effect of the Coulomb field of the nucleus will be deflected from its trajectory with a loss of energy. This energy will be emitted in the form of a photon of energy $h\nu$ known as Bremsstrahlung (braking radiation). The emitted radiation spectrum covers the entire energy range from zero up to the maximum kinetic energy of the passing electron. The Bremsstrahlung yield is proportional to the inverse square of the mass of the particle, and therefore is significant for light particles such as electrons. The rate of radiative losses is approximately proportional to the
electron energy and square of the atomic number of the absorber. This means that x-ray production through radiative losses is more efficient for high energy electrons and higher atomic number materials. Another category of radiative loss occurs when the passing electron interacts directly with an atomic electron of an inner shell and as a consequence shell electron is ejected and vacancy is left behind. Atomic electrons from upper energy levels fill up that vacancy and characteristic radiation is emitted as a result.

2.2 Stopping power

The linear stopping power is defined as the expectation value of the kinetic energy loss $E$ of a charged particle per unit path length $(dE / dx)$. The mass stopping power is defined as a function of the linear stopping power divided by $\rho$ (density of absorbing medium $\rho$), and is expressed as:

$$\frac{S}{\rho} = \frac{1}{\rho} \left( \frac{dE}{dx} \right) \quad (2.1)$$

The total mass stopping power $(S_{\text{tot}} / \rho)$ is subdivided into two components, collision stopping power $(S_{\text{col}} / \rho)$ resulting from interactions of charged particle with orbital electrons and radiative stopping power $(S_{\text{rad}} / \rho)$ resulting from interactions of charged particles with nuclei.

$$\frac{S_{\text{tot}}}{\rho} = \frac{S_{\text{col}}}{\rho} + \frac{S_{\text{rad}}}{\rho} \quad (2.2)$$

2.2.1 Collision stopping power

Berger and Seltzer [4] derived an analytical expression for the mass collision stopping power $(S_{\text{col}} / \rho)$. For events involving electrons and positrons the Bethe theory [5] for soft collision, is applied. For hard collisions events, in the case of
electrons, the Moller differential cross section for hard collisions is used, and in case of positrons, the Bhabba differential cross section for hard collisions is applied. The mass collision stopping power can be expressed as [6]:

\[
\frac{S_{\text{col}}}{\rho} = \frac{N_A Z}{A} \frac{\pi r_e^2 2m_e c^2}{\beta^2} \left[ \ln \left( \frac{E_k}{I} \right)^2 + \ln \left( 1 + \frac{\tau}{2} \right) + F^\pm (\tau) - \delta \right]
\]  

(2.3)

where

- \( r_e \) – is the classical electron radius (2.82 fm),
- \( I \) – is the mean excitation potential of the medium,
- \( \delta \) – is the density effect correction,
- \( \beta = \frac{v}{c}, \quad \tau = \frac{E_k}{m_e c^2}, \)

With \( F^- \) given for electrons as:

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

(2.4)

with \( F^+ \) given for positrons as:

\[
F^+ (\tau) = 2 \ln 2 - \left( \frac{\beta^2}{12} \right) \left[ 23 + \frac{14}{(\tau + 2)} + \frac{10}{(\tau + 2)^2} + \frac{4}{(\tau + 2)^3} \right]
\]  

(2.5)

The density effect correction accounts for the fact that collision stopping power decreases as a result of the polarization of the medium caused by the charged particle passage. The mean excitation potential \( I \) is a mean value of all ionization and excitation potentials of an atom in absorbing medium. Since it depends on the imparting charged particle type, values of \( I \) are often determined from measurements with heavy particles.
2.2.2 Radiative stopping power

The mass radiative stopping power is the rate of energy loss by electrons or positrons that results in production of Bremsstrahlung. The formula for the mass radiative stopping power is derived from Bethe-Heitler theory [7], and can be expressed as [3]:

\[
\frac{S_{\text{rad}}}{\rho} = \sigma_0 \frac{N_A Z^2}{A} \left( E_k + m_e c^2 \right) \overline{B}_r \quad (2.6)
\]

where \( \sigma_0 = 5.80 \times 10^{-28} \text{ cm}^2 / \text{atom} \), \( \overline{B}_r \) is a function of \( Z \) and \( E_k \), varying between 16/3 and 15 for energies in the range from less than 0.5 MeV to 100 MeV.

Mass collision stopping power and mass radiative stopping power for lead (high Z material) and water (low Z material) are graphed as a function of electron energy in Figure 2.3. Figure 2.3 shows that for low energies \( \frac{S_{\text{col}}}{\rho} \) is high and decreases inversely proportional to \( E_k \) of the charged particle until it reaches a broad minimum around energy \( 3M_{\text{absorber}}c^2 \) and beyond that minimum mass collision stopping power rises slowly with kinetic energy \( E_k \).

Mass collision stopping power is higher for low Z materials (water on the figure) though the entire energy range. This is attributed to the fact that low Z materials have slightly higher number of electrons per unit mass free to take part in collisions.

The mass radiative stopping power \( \left( \frac{S_{\text{rad}}}{\rho} \right) \) clearly shows an approximate proportionality to the atomic number \( Z \) of the absorber and the kinetic energy \( E_k \) of light charged particles (with kinetic energies above 2 MeV). Mass radiative stopping power is higher for high Z materials in entire energy range and should be noted that above 10 MeV the rate of radiative energy loss exceeds that of the
collision loss for high $Z$ materials. For interactions with tissue ($Z \approx 7.42$) we note that the $\frac{S_{\text{col}}}{\rho}$ is approximately constant at 2 MeV.

![Figure 2.2: Mass collision and radiative stopping powers for liquid water and lead [8].](image)

2.3 Physical and Clinical aspects of the Electron beams

2.3.1 Electron beam characteristics

2.3.1.1 General shape of depth dose curves

The basic information concerning the physical characteristics of an electron beam is obtained by measuring the dose distribution along the central axis of the beam as the function of the depth in water, or water equivalent solid material.

The Percent Depth Dose (PDD) is defined as:
\[ PDD(d, A, f, E) = 100 \times \frac{D(d)}{D(d_{\text{max}})} \]  \hspace{1cm} (2.7)

where

\( D(d) \) - is dose (or dose rate) at a point with depth \( d \) on the central axis of the phantom.

\( D(d_{\text{max}}) \) – is the maximum dose (or dose rate) at a point with depth \( d_{\text{max}} \) on the central axis of the phantom.

\( A \) – is field size.

\( f \) – is Source to Surface Distance (SSD).

\( E \) – is the energy of the beam.

The electron beam PDD curve is characterized by high surface dose followed by a small dose build-up, a broad \( d_{\text{max}} \) plateau, and sharp fall off of the dose until a second plateau is reached at a few percent of the maximum dose. This second plateau is called “Bremsstrahlung tail”, and it is uniquely due to photon contamination produced in the Linac head, in the air between accelerator window and in the irradiated medium. A few quantities of interest are defined on the electron PDD.

![Typical electron beam PDD curve](image)

Figure 2.3: Typical electron beam PDD curve [2].
As illustrated on Figure 2.3, the main parameters that describe an electron PDD curve include the surface dose, the depth of maximum dose, $R_{90}$ the depth of 90% dose called therapeutic range since it is used by radiation-oncologists for dose prescription, $R_{50}$ the depth of 50% dose used for beam quality specification and finally $R_p$ the practical range located at the depth of intersection of the slope of the PDD fall-off and of the Bremsstrahlung tail.

![Electron PDD cone 10x10 cm²](image)

**Figure 2.4**: Energy dependence of Percent Depth Dose (PDD) on Varian Clinac 21EX at SSD=100 cm measured with p-Si diode. Curves from left to right: 6 MeV, 9 MeV, 12 MeV, 16 MeV, 20 MeV.

The shape of the electron PDD curve depends on the energy of the incident beam, as illustrated on Figure 2.4. The higher the energy of the beam, the higher the surface dose, the broader the $d_{\text{max}}$ region, the less steep the dose fall-off, and the higher the contribution from Bremsstrahlung radiation. According to Figure 2.4 the contribution of the Bremsstrahlung radiation ranges from 0.7% for 6 MeV to 5.5 % for 20 MeV. The electron PDD curve also experiences field size dependence. For any field whose half dimension is larger than the range of the laterally scattered electrons, the PDD curves look similar due to existence of
lateral electronic equilibrium. However, for fields with one dimension smaller than the range of laterally scattered electrons, lateral electronic equilibrium is disrupted and low energy electrons deposit their energy close to the surface, and there exists a shifting of the PDD curve towards the surface. For oblique beam incidence with angles $\alpha$, defined between the beam central axis and the normal to the phantom surface, exceeding $20^0$, there are significant changes to the PDD shape. As the angle $\alpha$ is increased, $d_{\text{max}}$ moves towards the surface and the dose deposited at $d_{\text{max}}$ becomes larger. For small angles of incidence $\alpha$, the slope of the PDD curve decreases and the practical range is almost unchanged from that for normal beam incidence. When the angle of incidence $\alpha$, exceeds $60^0$ the shape of the PDD looses its characteristic shape and definition of $R_p$ can no longer be applied, and the dose at $d_{\text{max}}$ increases significantly. This effect is due to the increased electron fluence through the central axis.

2.3.1.2 Isodose curves

The information provided by the central axis depth dose is not sufficient to characterise the radiation distribution produced by the radiation beam in space. In practice, two-dimensional isodose lines are used for beam presentation in any given plane. These lines pass through points with equal dose, usually drawn for equal increments of percentage depth dose, normalised to a reference point, which is usually taken at $d_{\text{max}}$ on the beam central axis. There are two phenomena that should be mentioned: bulging and constricting of isodose curves. Bulging is characteristic of electron beam isodose curves for low value isodose curves, less than 20 %, and it is a direct result of the increase in electron scattering angle with decreasing electron energy. At energies above 15 MeV, higher value isodose curves, above 80%, exhibit a lateral constriction. This is a consequence of a loss of charged particle equilibrium (CPE) due to the lack of low energy electrons near the field edges at these depths. Both effects are illustrated in Figure 2.5.
Figure 2.5: Isodose curves for 9 MeV and 20 MeV electron beams. SSD = 100 cm and field size 10x10 cm² [2].

2.3.1.3 Dose profiles and off-axis ratios

A plot of off-axis ratio (OAR) against the distance from the central axis is referred to as a dose profile. Beam profiles are measured in water or water-equivalent solid material, along the beam central axis at a certain depth in direction perpendicular to the beam. Examples of beam dose profiles at specific depths for 12 MeV electron beam are given in Figure 2.6.
2.3.2 Electron beam energy specification

The energy spectrum of an electron beam, before it passes through the accelerator exit window is relatively narrow peak and can be characterised with a single energy value. This is usually referred as “accelerator nominal energy”. After passage through accelerator exit window energy distribution became more complex and there is a need for several parameters to be used to describe the electron beam energy spectrum. In general, they are:

\[ E_{p,0} \] – is the most probable energy on the phantom surface,

\[ \bar{E}_0 \] – is the mean energy on the phantom surface,

\[ R_{50} \] – is the depth in phantom at which absorbed dose fall to 50% of the maximum dose.

\[ R_e \] – is the practical range of electrons in water
The most probable energy at the surface $E_{p,0}$ and $\bar{E}_0$ mean energy at the surface, both expressed in MeV, can be determined from $R_p$ and $R_{50}$ (both expressed in cm), using the equations [9]:

$$E_{p,0} = 0.22 + 1.98R_p + 0.0025R_p^2$$  \hspace{1cm} (2.8)

$$\bar{E}_0 = C \cdot R_{50} \text{ where } C = 2.33 \text{ MeV/cm for water}$$  \hspace{1cm} (2.9)

The mean energy $\bar{E}_z$ at the given depth $z$, in a water phantom, is related to the practical range $R_p$ through Harder's relation [10]:

$$\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)$$  \hspace{1cm} (2.10)

### 2.3.3 Field shaping of electron beams

The collimation of electron beam is achieved by using electron applicators (cones). However, in clinical practice radiations fields of irregular shape are used that can be created by shielding blocks or cutouts, which are placed directly over the patient or attached to the end of the applicator (cone). When the cutout is used to shape the field, the electron field is defined at a distance as small as 5 cm away from the patient. Several applicators are provided, with different sizes, usually with square field shapes ranging from 5x5 cm² to 25x25 cm². For more customised field shapes, two materials are employed most frequently for shielding: lead or a low melting temperature alloy (Cerrobind). In this thesis work Cerrobend was used as a shielding material for the cut-out inserts.
References:

Chapter 3: Macro Monte Carlo

3.1 Introduction to Monte Carlo

The technique having potential to achieve the highest level of accuracy in dose calculation is Monte Carlo. The Monte Carlo method is a statistical simulation process that allows a highly accurate simulation model of a linear accelerator (Linac) or any other radiation source. The Monte Carlo method can model physical processes involved in radiation therapy. Starting with particle fluencies of the radiation beam, subsequently detailed radiation transport in voxel geometry can be modeled to determine dose distributions in patients [1] [2] [3] [4]. At the patient modeling stage, usually all tissue density heterogeneities and interfaces are taken into account. In particular, Monte Carlo can handle backscatter from high-density materials such as bone or scatter perturbations introduced by air cavities more accurately than any other currently existing dose calculation algorithm. An important difference between Monte Carlo (MC) simulations and all the other dose calculation models is that MC can calculate dose to actual tissue (bone, lung, etc.) inherently, whereas other techniques report dose to water within overall patient geometry [5].

3.2 Basics of Monte Carlo simulation

In order to use Monte Carlo as a radiation dose calculation model, a detailed simulation of individual particle interactions and tracks throughout the whole geometry of interest is required. Since, this method has the potential to take into account all possible interactions that a particle could experience passing through medium, Monte Carlo models the reality in a more “native” way compared with the analytical techniques used in other dose calculation models. The major limitation of MC modeling to become more applicable in commercial Treatment Planning Systems (TPS) is computer speed. Recently computers have become fast enough to allow Monte Carlo model to be used in the field of medical physics for clinical...
applications. In order to perform a Monte Carlo simulation for radiation dose calculation, accurate knowledge of interaction cross sections and probability distributions for photon and electron interactions is necessary for all materials involved in that simulation. In practice, these distributions are sampled randomly though the use of a Random Number Generator (RNG) [5].

To achieve accurate results from a Monte Carlo simulation there are two important components that must be precisely modeled: (1) The radiation source and (2) particle transport in patient geometry. The composition and geometry of both have to be well known [6]. For the radiation source, geometry is obtained from manufacturer specification and patient geometry is determined from Computed Tomography (CT) scans. Figure 3.1 represents schematic diagram of the Monte Carlo simulation process.

3.3 Physical processes to model in Monte Carlo

Different Monte Carlo codes vary in the different physical processes they model and degree of accuracy achieved. For radiotherapy applications, transport of photons and electrons should be performed by modeling the relevant processes.

![Figure 3.1: Structure of a Monte Carlo simulation](image)
3.3.1 Electron interactions

A detailed overview on physics of the electron interactions with matter was made in Chapter 2. In this chapter electron interactions are going to be mentioned only to clarify their implications in the Monte Carlo technique.

- *Bremsstrahlung production* - is mainly important for high-energy electrons and high-Z materials. This is vital process to be modeled in Bremsstrahlung target of a Linac and the Linac head components.

- *Möller electron-electron scattering* – these are close electron-electron collisions also referred as knock-on collisions and they can result in production of a delta electrons which are added to the electron shower [7].

- *Molière multiple elastic scattering* - Molière theory [8] [9] was originally developed as small-angle theory for multiple scattering events through Coulomb processes mostly with the nuclei, and is intended to be used for multiple-scattering deflections not larger than about 20 degrees. The Molière distribution is a function of a scaled angular variable, which simplifies the random sampling, and makes it easy to select multiple-scattering deflections for randomly selected path lengths. Since the theory does not account for spin and relativistic effects, it leads to an underestimate of the scattering angles for low-energy electrons in high-Z materials [10].

3.4 Monte Carlo transport of electrons

In principle, electron transport is a lot more complicated than photon transport because electrons can interact with every electron of every atom they encounter and electron typically experience millions of interactions before loosing all their kinetic energy. Modelling of such process is not impossible in practice but is not usually
required in most radiotherapy applications. Such a microscopic resolution is required only in some special cases when radiation damage to DNA is investigated.

For radiation therapy applications usually a number of electron collisions are grouped using multiple scatter theory. Electron step length is sampled using multiple scatter theory and at the end of each step probability distributions are sampled to determine type of discrete interaction that takes place, production of delta electron or Bremsstrahlung photon. Electron transport is terminated when their energy has reached the transport cut-off energy or when they leave region of interest. Figure 3.2 shows the essential steps for Monte Carlo transport for electrons.

3.5 Electron Monte Carlo (eMC) Algorithm

Main purpose of this work is to commission a commercial treatment planning system (TPS) Eclipse™, manufactured from Varian Medical Systems, Inc. (VMS, Las Vegas, NV). Eclipse™ uses eMC algorithm for dose distribution calculation from high-energy electrons. The electron eMC algorithm is a fast implementation of the Monte Carlo method. The algorithm consists of:

- **Electron transport** – dose deposition model (Macro Monte Carlo method [11], MMC) performing the transport and the dose deposition caused by the electrons in patient geometry.

- **Radiation source** – electron beam phase-space model (Initial Phase Space, IPS) modeling the electrons that emerge from the treatment head of the Linear accelerator.
Figure 3.2: Simplified electron transport algorithm [5].
3.5.1 Electron transport model (MMC)

In Eclipse™ electrons are transported using Macro Monte Carlo (MMC) method, which is an implementation of the Local-to-Global Monte Carlo (LTG MC) method. Basically, LTG MC Method is a two-step procedure [11], calculations in a Local geometry and calculations in a Global geometry.

A. Calculations in Local Geometry

Conventional Monte Carlo simulations of electron transport are performed in a well-defined local geometry based in small radius about the calculation point. These calculations result in a library of Probability Distribution Functions (PDFs) of particles emerging from the local geometry. These PDFs are calculated only once for variety of clinically relevant materials and energies and stored in MMC database.

The PDFs for local geometry calculations are generated in extensive pre-calculations by employing the Electron Gamma Shower Version 4 (EGS4, EGSnrc) code system [12] to simulate the transport of vertically incident electrons of variable energies through macroscopic spheres of sizes and materials likely to be used for actual MMC simulation. The MMC method uses spherical volume elements, for the local calculations. Figure 3.3 shows local sphere with all parameters kept in MMC Database.

For primary electrons, the MMC database contains PDFs for the exit position \( \alpha \), the direction \( \theta \) and the energy \( T_f \) of the emerging primary electron. There is one PDF for each of the parameters for any combination of 5 different materials, 5 sphere radii \( r \) and 30 incident energy values \( T_i \). Values for these materials, sphere radii and incident electron energies are listed in Table 3.1.

For secondary particles (electrons and photons), emerging from the sphere, only the average energy transferred to these particles is stored as a function of the incident primary electron energy \( T_i \). There is no position or direction parameters stored in MMC database for secondary particles.
Figure 3.3: Local Geometry Used in MMC

<table>
<thead>
<tr>
<th>Five clinically relevant materials</th>
<th>Five sphere radii ( r ) (mm)</th>
<th>Thirty incident energy values ( T_i ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.5</td>
<td>0.2, 0.4, 0.6</td>
</tr>
<tr>
<td>Lung phantom (LN4)</td>
<td>1.0</td>
<td>0.8, 1.0, 1.5</td>
</tr>
<tr>
<td>Water</td>
<td>1.5</td>
<td>2.0, 3.0, 4.0</td>
</tr>
<tr>
<td>Lucite</td>
<td>2.0</td>
<td>...</td>
</tr>
<tr>
<td>Solid bone phantom (SB3)</td>
<td>3.0</td>
<td>23, 24, 25</td>
</tr>
</tbody>
</table>

Table 3.1: List of clinically relevant materials, sphere radii, and primary electrons incident energy values used for PDFs pre-calculations.
B. Calculation in Global Geometry

Monte Carlo calculations are performed in a global geometry for a specific absorber. Electrons are transported through the absorber in macroscopic steps based on the PDFs generated in the local calculations. For MMC sphere-by-sphere transport to work correctly, it is necessary to know the size and mean density inside the spheres used for the transport steps. The embedded adaptive step size algorithm determines the sphere sizes and mean sphere densities at each position in the absorber by pre-processing the whole absorber CT volume prior to MMC simulation. The CT volume is first converted into electron density volume, applying appropriate CT-to-electron density conversion factors and then the resulting volume is scanned for heterogeneity. To each voxel of the density-volume, a sphere index is assigned that corresponds to the maximal sphere radius that can be used from the current voxel center without the corresponding sphere reaching into the other material. This process therefore results in small sphere sizes assigned to voxels near interfaces between different materials and large sphere sizes assigned to voxels at larger distances from such interfaces, as can be seen on Figure 3.4. A voxel of the density volume is considered to be part of a heterogeneity area if the density ratio of the voxel and its neighbours exceeds a limit 1.5. If the densities in both voxels are below a user controlled threshold (typical value 0.05 g cm$^{-3}$), the ratio is not evaluated. This density threshold prevents noise in low density data being interpreted as heterogeneity. For density ratios below the limits mentioned above, the MMC algorithm is capable of processing differences in the material without decreasing the step size. This fact allows to MMC algorithm to reduce the time required for MC simulation.

Another feature of the adaptive step size algorithm is the ability to stop a particle at an interface between different materials, and to restart the transport with a new sphere in the new material, preserving the particle's direction of motion. Stopping at interfaces is only necessary if the ratio of linear stopping powers on both sides of the interface exceeds a certain limit (typical value 1.5). The stopping power feature is
very important to obtain reasonable dose distributions in near air heterogeneities. Boundary crossing method is illustrated in Figure 3.4.

Figure 3.4: The adaptive step size algorithm (2D illustration for a density volume of 0.1 cm resolution) [11].

Energy deposited from primary electrons is along a straight line from the point where the electron enters the sphere to the point where it leaves (dotted lines inside the spheres on Figure 3.4). A ray trace between these two points is performed by a modified Siddon ray trace algorithm [13] through the voxels of the dose volume. The energy deposition due to secondary particles (electrons and photons) released in a sphere in each MMC step is not transported, but stored in those voxels where secondary energy deposition has been released. Transport and deposition of these dose contributions are handled by post processing of the secondary energy deposition volumes after the actual simulation. This approach results in an appreciable increase in speed of the simulation.
3.5.2 Initial Phase Space (IPS) Model

IPS model is the way eMC algorithm models the electrons that emerge from the treatment head of the linear accelerator. IPS is a distribution in position, energy and direction of electrons and photons in a plane above the patient. The location of the IPS plane is specified to be at the lower end of the electron applicator. Here the IPS takes into account field shape of the applied cutout. This fact results in an IPS that differs for specific combination of electron beam energy and applicator. It is assumed that the IPS can be adequately described by the sum of four simplified beam components. Each of them accounts for part of the electron or photon fluence in the IPS plane. By adequately derived parameter values and weights for these components, a description of the IPS emerges that is sufficient as input for electron beam dose calculation [14]. These four beam components are: (1) Main diverging beam, (2) Applicator scatter, (3) Applicator transmission, (4) Second diverging beam. See Figure 3.5.

![Schematic view of the directional distribution of the four beam components](image)

**Figure 3.5:** A schematic view of the directional distribution of the four beam components that are used to model the IPS of a clinical electron beam [14].
3.5.2.1 Main diverging beam

The first component, the main diverging beam, forms the prominent part of a clinical electron beam. This component models the electron and Bremsstrahlung photons that do not interact with any other part of the accelerator head besides scattering foils, monitor chamber and air before passing throughout the open part of the applicator diaphragm. The distance of the focus is 10 cm below the nominal source and the particle are sampled on the plane located 95 cm inside the shape defined by the applicator or insert (Figure 3.5a). It is presumed that the directional distribution of the electrons and photons of the main diverging beam are adequately described by the directional distribution of a diverging beam with an angular variance [15]. It is also assumed that this main diverging beam remains identical with respect to its direction and energy distribution for different electron beam applicators, for specific clinical accelerator energies.

3.5.2.2 Applicator scatter

The second component, applicator scatter, models the electrons that scatter from the edge of the lower applicator as the result of interactions in the lower applicator or the insert. This component reflects the fact that the edge of the lower applicator or cutout is an important source of scattered electrons (Figure 3.5b). Applicator scatter is adequately described by integrating a point spread kernel of electrons and photons along the diaphragm edge. Only one point spread kernel is applied to describe the direction and energy distribution of scattered particles, and it simulates the scattered particles at every position along the edge. Differences between scattered particles at different positions along the edge are neglected. As a result of this applicator scatter sub-source is a line source along the cutout of the applicator.
3.5.2.3 Applicator transmission

The third component, *applicator transmission*, models the photons and electrons transmission through the lower applicator as the result of impact of electrons and photons on the applicator itself. This component models the fact that the lower applicator or cutout insert does not stop all electrons and photons outside the open part of the applicator diaphragm (Figure 3.5c). Photon transmission can account for a few percent of the dose in the region outside the main beam area. In Eclipse™ three types of transmission photons are taken into account. (1) Scattered photons produced by electrons from *main diverging beam* impinging the cutout material. (2) Scattered photons produced by photons from *main diverging beam* scattered in the cutout material and (3) Main photons passing through the cutout material without interaction, they have the same direction as photons from *main diverging beam* but a different energy distribution.

3.5.2.4 Second diverging beam

The first, second and third components of the model should closely model particles that are present. The fourth component, the *second diverging beam*, models the electrons and photons that have interacted with various other parts of the Linac head before passing through applicator diaphragm, and are not modeled by the first three components (Figure 3.5d). In reality, these electrons and photons do not emerge from a single point source but come from sources like the jaws, scrapers or applicator walls. In Eclipse™ this *second diverging beam* sub-source is modeled with virtual point source. The particles are sampled on a plane 95 cm inside the shape defined by the applicator or cutout insert. Modeling of these scattered electrons as point source is a coarse approximation, because whenever cutout is applied to shape the beam or the SSD is changed, the fluence of the scattered electrons from various parts of the Linac head will be reduced. This is the main reason the *second diverging beam* module has to allow adjustable beam weights
which depend on the relevant applicator, on the cutout and on the actual source to surface distance (SSD).

References:

Chapter 4: Materials and Methods - Equipment

4.1 Linear accelerator and Accessories

All measurements in this study were performed with a CL 21 EX Linear accelerator (Clinac) (Varian Oncology Systems, Palo Alto, CA) installed and commissioned in the Radiation Oncology Department at McGill University Health Center in 2001. The CL 21 EX is designed to provide photon beams with nominal energies of 6 MV and 18 MV, as well as electron energies of 6, 9, 12, 16 and 20 MeV. Electrons are accelerated to kinetic energies from 6 to 20 MeV using non-conservative microwave radiofrequency (RF), at 2856 MHz located in the S band frequency range. Both energy modalities of the clinical photon beams are produced by allowing the pencil electron beam to strike a copper made x-ray target. The radiative losses in the target (Bremsstrahlung) from these interactions produce the high energy photon beams. In order to obtain a flat beam a flattening filter is used to preferentially attenuate the photon beam at the central axis.

Electron beams are produced by retracting the target and the flattening filter from electron’s path, and replacing them with a scattering foil. A dual ionization chamber is used to monitor the beam output and symmetry during the beam delivery.

The CL 21 EX is isocentrically mounted with a Source-to-Axis Distance (SAD) = 100 cm. The dose rate supplied by the CL 21 EX varies from 100 to 1000 MU/min in increments of 100 MU/min.

In this study all measurements were done with collimator rotated by $90^0$ and the photon collimator settings were automatically adjusted by the machine according to the electron applicator inserted. The dose rate was consistently set to be 400
MU/min in order to avoid issues with dose rate dependence of the detectors response and fluctuations of the Linac output with dose rate.

The output of the Linac was calibrated according to recommendations of the TG-51 protocol [1], to be 100 cGy/100 MU ± 2 % in water phantom at $d_{\text{max}}$ for a 10 x 10 cm$^2$ applicator. The absolute calibration of a CL 21 EX in water phantom is performed once a year as a part of the clinical Quality Assurance (QA) program. In order to monitor the stability of the output of the machine routinely twice a week photon and electron beam constancy check in solid water phantom is performed under the same reference conditions.

For electron beam delivery applicators with cutout inserts are used to collimate the beam aperture. The electron applicators available for CL 21 EX are as follows: 6 x 6 cm$^2$, 10 x 10 cm$^2$, 15 x 15 cm$^2$, 20 x 20 cm$^2$ and 25 x 25 cm$^2$.

Cutout inserts are used to shape the electron beam to the tumor with a purpose of minimizing the dose delivered to the surrounding healthy tissues. For this study all applicators with standard cutout inserts (6x6, 10x10, 15x15, 20x20 and 25x25 cm$^2$) were used with electron beams with nominal energies 6, 9, 12, 16 and 20 MeV.

Cutouts with various shapes were designed for this project as well. Both large and small field sizes were studied. Ten regularly shaped cutouts were designed. Five of them were with circular shape ranging from 1 cm to 5 cm in diameter. The cutouts ranging in sizes from 1 cm to 4 cm were designed to fit in the 6 x 6 cm$^2$ applicator and the cutout with diameter 5 cm was made to fit in the 10 x 10 cm$^2$ applicator. The other five regularly shaped cutouts were rectangular type with dimensions as follows: 10x1 cm$^2$, 8x2 cm$^2$, 8x3 cm$^2$, 8x4 cm$^2$ and 8x5 cm$^2$ all of them designed to fit in the 10 x 10 cm$^2$ applicator. Three irregularly shaped cutout inserts, were also designed and all of them fit in 10 x 10 cm$^2$ applicator. Figure 4.1 shows examples of cutouts investigated in our study.
Figure 4.1: Examples for cutouts investigated. (a) example for circular shaped cutout 5 cm diameter. (b) example for rectangular shaped cutout 8x3 cm². (c) example for irregular shaped cutout.

Cutouts were made of low melting temperature lead alloy (cerrobend) which contains bismuth (50.0%), lead (26.7%), tin (13.3%) and cadmium (10.0%) and has a melting point 70 °Celsius. To manufacture the cutouts with all required different shapes previously described thirteen Styrofoam® pieces modeling the apertures were cut with required shape and dimensions. Each of them was placed inside the different cutout tray at required position. Melted cerrobend was poured in the trays and left for about 2 hour to cool. The Styrofoam pieces were removed from the cooled cutouts. The thickness of the cerrobend poured into cutout inserts was 1.5 cm, sufficiently thick enough to absorb the highest (20 MeV) electrons energy available. Since, the maximum range of the 20 MeV electrons in cerrobend is approximately 1 cm.

4.2 Radiation detectors

4.2.1 Scanditronix p-Si diode

The electron field detector (EFD) diode is a high-doped p-type silicon diode with a 0.5 mm thick chip, a 2.0 mm diameter active area, a waterproof encapsulation
and a displacement of the effective measurement point from the detector front surface of 0.55 mm. The small collecting volume of the diode, about 0.2-0.3 mm$^3$, along with a favorable signal-to-noise ratio motivated the decision for a p-Si diode to be used as a measuring device to measure profiles and percent depth doses (PDD's) especially for small fields or regions with steep dose gradients. Furthermore, the ratio between the electron stopping power in silicon and in water is constant for electron energies between 5 and 20 MeV for broad beams [2], hence, it is unnecessary to correct the percent depth ionization (PDI) for its variations to obtain percent depth dose (PDD). Generally diodes were used to measure PDD and profiles of small and irregular fields.

4.2.2 Ionization chamber – PPC 40

In our study a waterproof plane-parallel ion chamber PPC40 (Wellhöfer, Dosimetrie) was used to validate some of the PDD measurements performed with p-Si diode [3]. PPC40 is a Roos type ion chamber with collecting electrode diameter of 16 mm and guard ring of 4 mm width. The front window thickness is 1 mm (118 mg/cm$^2$) graphite coated Polymethyl Methacrylate (PMMA), electrode spacing of 2 mm and measuring volume 0.35 cm$^3$

With regards to reference dosimetry, plane-parallel chambers are recommended to be used for all electron energies, and their use for electron beams below 10 MeV is mandatory [4]. One of the main advantages of using plane-parallel chambers for electron beam dosimetry is the possibility of minimizing scatter perturbation effects. Plane-parallel chambers are designed so that the chamber samples incident electron fluence through the front window and the contribution of the electrons entering through side walls to be negligible (due to the guard ring). For plane-parallel chambers, the center of the front (upstream) face of the chamber air cavity is the point of measurement for all beam qualities and depths, based on TG-51 report recommendations [1]. For our measurements PPC40 was operating with a positive polarity potential difference applied to the chamber of
+300 V. The PDI curves were converted to dose by multiplying raw ionization readings by corresponding stopping power values for the specific depth and energy.

4.2.3 Ionization chamber – Advanced Markus

The Advanced Markus ionization chamber type (PTW-Freiburg, Germany) is another plane-parallel chamber. It has the same external dimensions as the Classic Markus (30 mm diameter x 14 mm thickness) but it has a smaller measuring volume of $0.02 \text{ cm}^3$ and an improved guard ring design of 2 mm reducing the influence of the scattered radiation from the housing. The collector electrode element is 5 mm in diameter and it is made of a graphite coated surface of a solid PMMA with 0.5 mm thickness. The entrance window material is polyethylene of 0.03 mm thickness with a plate separation of 1 mm. The chamber comes with a protective acrylic cover of 0.87 mm thickness (1 mm water equivalence) for use in water.

The Markus style of chamber has been designed specifically for electron beam dosimetry and has a small measuring volume ($0.02 \text{ cm}^3$) compared to that of the Roos type chambers (PPC40 ($0.35 \text{ cm}^3$)). This fact is an advantage in small-field dosimetry, resulting in improved spatial resolution. Advanced Markus chamber was employed in Relative Output Factors (ROF) measurements in a water phantom.

4.2.4 Ionization chamber – IC 10

The IC 10 (Wellhöfer, Dosimetry) is a waterproof cylindrical ionization chamber. This type of chamber may be used for the calibration of radiotherapy beams or routine measurements for medium energy X-rays with HVL 2 mm of aluminum, $^{60}\text{Co}$ gamma radiation, high energy photon beams, electron beams,
and therapeutic proton and heavy ion beams. The cavity volume of the IC 10 is 0.14 cm$^3$ with cavity radius of 3.0 mm. The material used for outer chamber wall and central electrode is C-552 (Shonka Conductive C-552 plastic) with a wall thickness of 0.068 g/cm$^2$ [4]. This type of chamber is very convenient for measurements because it is robust and simple to use in a water phantom. In our study the IC 10 ion chamber was used for Eclipse Beam configuration water tank measurements.

4.3 Film dosimetry – Gafchromic® film

The introduction of radiochromic dye-cyanide films has solved some of the problems experienced with conventional radiation dosimeters [5]. The EBT model (External Beam Therapy) high sensitivity radiochromic film has been tailored for absorbed dose measurements in high-energy photon and electron beams (above 1 MeV). The film is designed to be used in a dose range from 1 cGy to 800 cGy and, like all radiochromic films, is relatively insensitive to visible light, so it can be easily handled in day-light conditions. The high spatial resolution and low spectral sensitivity, make radiochromic films ideal for the measurement of dose distributions in regions of high dose gradient as well as surface dose measurements. The structure of the EBT film model consists of two sensitive layers, each having thickness of 17 μm and separated by a 6 μm thick surface layer (Figure 4.2). The overall atomic composition of the EBT GafChromic® (International Specialty Products, Wayne, NJ) film model is H-39.7%, C – 42.3%, O – 16.2%, N – 1.1%, Li – 0.3% and Cl – 0.3% by weight, as quoted by the manufacturer [6].
4.3.1 EBT GafChromic® film - calibration procedure

The film dosimetry system used in this study consists of three components: film-EBT GafChromic®, the scanning densitometer – a flat-bed document scanner AGFA Arcus II and a scanning protocol described in [6]. Prior to use for measurements EBT film must be calibrated in order to determine a relationship between changes in net optical density (\(netOD\)) versus delivered dose (\(D\)).

Each 5 cm x 10 cm film piece was irradiated in a solid water phantom at \(d_{\text{max}}\) perpendicularly to the radiation beam for each particular energy. With the purpose of providing sufficient backscatter, a 15 cm thick piece of solid water was placed below the films. The field size used was 20 cm x 20 cm at SSD = 100 cm and a Farmer type monitor chamber was placed within the same phantom below the film in order to measure the output of the Linac. The EBT films were exposed to the following doses: 0, 0.3, 0.5, 0.75, 1, 2, 3, 4, and 5 Gy. Dose delivered to the film was calculated from the output for a given beam modality, using the TG-51 protocol. Dose represents dose to water and we assume that the film is water equivalent and that the presence of the solid water phantom...
does not perturb the fluence of the electron beam. Hence, no conversion factor from the dose to water (based on TG-51) to the dose to the film has been applied.

The first step in the protocol for GafChromic® film calibration is to scan the unexposed pieces of film 3 times in order to remove the scanner noise by averaging of scanned images. The films were scanned in the 48-bit RGB mode (16 bits per color) and saved as tagged image file format (TIFF) image files. Blank scans were also taken (3 times) over the same region of the scanner where previously unexposed film pieces were placed.

Once irradiated, the films were left for a period of 24 h to self-develop, and then they were scanned again with same orientation as they were before irradiation (3 times). The scanning resolution used was 127 dpi, which corresponds to 0.2 mm/pixel. The region of interest (ROI) over which the change in optical density was sampled was 21 by 21 pixels, e.g., 4 mm x 4 mm.

Once sets of images were obtained, the images were imported into an in-house image manipulation routine written in Matlab 7.0 (Mat Works, Natick, MA) to extract the red component of the RGB scanned image because the maximum absorption band for the EBT model is centered at 633 nm. An average over the five ROIs per film piece was then obtained, and was used for the netOD calculation.

For densitometers that do not read OD directly, the netOD$^i(D_j)$ for a dose $D_j$ can be calculated as follows:

$$netOD^i(D_j) = OD_{\text{exp}}^i(D_j) - OD_{\text{unexp}}^i(D_j) = \log_{10} \frac{I_{\text{unexp}}^i(D_j)}{I_{\text{exp}}^i(D_j) - I_{\text{bkg}}}$$ \hspace{1cm} (4.1)

Where $I_{\text{unexp}}^i(D_j)$ and $I_{\text{exp}}^i(D_j)$ are the readings from for unexposed and exposed piece of film for the $i$th region of interest, respectively.

$I_{\text{bkg}}$ - is the zero-light transmitted value, which characterizes the background signal of the scanner.
Delivered dose \( (D) \) versus measured \( netOD \ (D) \) was fitted using the analytical form:

\[
D_f = b \cdot netOD + c \cdot lnOD \quad (4.2)
\]

In order to perform curve fitting we followed the approach described in [7]. A typical calibration curve for EBT GafChromic® film is shown on Figure 4.3.

![Calibration curve 12 MeV electron beam](image)

**Figure 4.3: Typical calibration curve (EBT GafChromic®) for 12 MeV electron beam.**

**4.4 Phantoms**

**4.4.1 Water phantoms**

Water is recommended in TG-51, as the reference medium for measurements of absorbed dose for both photon and electron beams.

Two dosimetry systems for 3D radiation field analysis were employed in this study, Radiation Field Analyzer (RFA-300) (Scanditronix, Uppsala, Sweden), and
WP700 (Wellhöfer, Schwarzenbruk, Germany). Some important technical characteristics of these phantoms are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>WP 700</th>
<th>RFA-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning volume:</td>
<td>480 mm (L) x 480 mm (W) x 410 mm (H)</td>
<td>495 mm (L) x 495 mm (W) x 495 mm (H)</td>
</tr>
<tr>
<td>Scanning speed:</td>
<td>Up to 15 mm/s</td>
<td>15, 30, 50 mm/s</td>
</tr>
<tr>
<td>Position reproducibility:</td>
<td>Min. 0.1 mm</td>
<td>+/- 0.1 mm</td>
</tr>
<tr>
<td>Position accuracy:</td>
<td>+/- 0.5 mm</td>
<td>+/- 0.5 mm</td>
</tr>
<tr>
<td>Approximate volume:</td>
<td>200 liters</td>
<td>206 liters</td>
</tr>
<tr>
<td>Weight:</td>
<td>46 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td>Wall material:</td>
<td>Acrylic (plexiglass)</td>
<td>Acrylic (plexiglass)</td>
</tr>
<tr>
<td>Detector holder:</td>
<td>PVDF</td>
<td>PVDF</td>
</tr>
</tbody>
</table>

Table 4.1: Technical parameters of the two water tanks (WP700 and RFA-300) employed in dose distribution measurements.

4.4.2 Solid water phantom

Solid Water™ is designed for electron and photon beam measurements including relative ionization, depth dose and uniformity. The Solid Water is epoxy resin-based solid rigid substitute for water. This material is comprised of epoxy resin, calcium carbonate, polyethylene, and phenolic micro spheres [8]. The elemental composition of the Solid Water (RMI-457) is: H (8.09%), C (67.22%), N (2.4%), O₂ (19.84%), Cl (0.13%), and Ca (2.32%) with density 1.030 g/cm³ and effective atomic number Z = 5.96. The slabs with dimensions 30x30 cm are most widely used with thickness varying from 0.2 cm to 6 cm and are considered to be a
standard size. Solid Water slabs were used with EBT GafChromic film measurements.

References:

Chapter 5: Commissioning Eclipse™: Data requirements and validation measurements

Beam data collection, configuration, and validation for clinical use are critical elements of commissioning a new treatment planning system. Users of the Eclipse™ have two possible approaches for the input of beam data into the system:

- Beam data provided with Eclipse™ for Clinac 21/23 EX treatment machines- referred to as Golden Beam Data (GBD).

- Beam data collected on-site by the physicist.

Golden Beam Data is a standardized set of beam scans and other data which, for a given beam modality and energy, constitutes the minimum required beam data for configuring the Eclipse™ treatment planning system for dose calculation.

5.1 Data requirements

5.1.1 Linac and Accessory specification

5.1.1.1 Beam configuration

When starting the configuration of the Eclipse™ TPS first the treatment unit must be created and configured. Next, each accessory including electron applicators, and cutout inserts (considered an add-on device of the accelerator), must be configured.

The next step is the definition of the general and the model parameters of the treatment unit.
The eMC algorithm requires the following general treatment unit parameters before importing measured beam data: nominal beam energy and treatment unit name.

The model parameters required from Eclipse™ are read from the installed Data Type Specification file of the eMC algorithm. These parameters are machine type, regularization of the low energy region, linearization of the low energy region, regularization of the peak and peak width in (MeV).

When the treatment unit, add-ons (applicators) and energy parameters have been defined, measured beam data can be imported in the Waterphantom-CadPlan file format for water phantom (w2CAD) data. Measured beam data (depth dose, profiles) must be imported for each add-on (applicator) that we wish to use in treatment planning. Measured beam data requirements will be discussed in more detail in section 5.1.2.

The Beam Configuration task generates the configured beam data for the selected add-on (applicator) from the measured beam data imported for the treatment unit.

5.1.1.2 Geometrical parameters and Limitations

To prevent creating a plan that would be impossible to treat on the accelerator, certain geometrical limits can be set for each treatment unit such as, limits of the gantry, table and collimator rotations.

For Varian accelerators, Eclipse™ sets the geometrical parameters and limitations automatically, so the user does not need to enter them separately.
5.1.1.3 Beam Calculation options

The eMC code is configured in Eclipse™ as an additional dose calculation server. The user has the option to select the eMC algorithm as the dose calculation model from within the software. The user has six parameters to be set for individual calculations: calculation grid size, calculation accuracy, maximum number of particle histories, random number generator seed, smoothing method and a smoothing level.

The parameters and their ranges of values are given in Table 5.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation grid size</td>
<td>1 mm, 1.5 mm, 2 mm, 2.5 mm, 5 mm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1%, 2%, 3%, 5%, 8%</td>
</tr>
<tr>
<td>Maximum number of particle histories</td>
<td>≥0</td>
</tr>
<tr>
<td>Random number seed generator</td>
<td>1 to 2100000000</td>
</tr>
<tr>
<td>Smoothing method</td>
<td>No smoothing</td>
</tr>
<tr>
<td></td>
<td>2-D Median</td>
</tr>
<tr>
<td></td>
<td>3-D Gaussian</td>
</tr>
<tr>
<td>Smoothing level</td>
<td>1-Low</td>
</tr>
<tr>
<td></td>
<td>2-Medium</td>
</tr>
<tr>
<td></td>
<td>3-Strong</td>
</tr>
</tbody>
</table>

Table 5.1: Example of Eclipse™ electron Monte Carlo calculation parameters.
The **Calculation grid size** has five present values (mentioned in Table 5.1). Popple et al. [1] discovered that the good results are obtained for grid spacing that are approximately one-fifth to one-tenth of the distance from 80% to 20% in distal falloff ($R_{80-20}$). For 6 MeV we obtained good results with 1.0 mm grid size, 9 MeV with 1.0 mm or 1.5 mm grid sizes, for 12 MeV 2.0 mm grid size and for 16 MeV and 20 MeV with 2.5 mm grid size.

The **Accuracy** parameter has five available settings values, previously mentioned in Table 5.1. The eMC defines the overall **Accuracy** as the *average statistical uncertainty* in all in the region of interest. The region of interest contains all voxels within the body or phantom contours with a dose larger than 50% of the maximum dose $d_{\text{max}}$. The *average statistical uncertainty* $S_{50}$ is calculated using formula 5.1 [2]:

$$S_{50} = \frac{1}{N_{50}} \sum D_{ijk} > 50\% d_{\text{max}} \frac{\Delta D_{ijk}}{d_{\text{max}}}$$ \hspace{1cm} (5.1)

Where

$N_{50}$ is a number of voxels satisfying the condition $D_{ijk} > 50\% d_{\text{max}}$.

$\Delta D_{ijk}$ are the statistical uncertainties and they are calculated employing following formula:

$$\Delta D_{ijk}^2 = \frac{\left\langle D_{ijk}^2 \right\rangle - \left(\left\langle D_{ijk} \right\rangle \right)^2}{N_{\text{batch}} - 1}$$ \hspace{1cm} (5.2)

Where

$\left\langle D_{ijk} \right\rangle$ is the average dose.

$\left\langle D_{ijk}^2 \right\rangle$ is the average dose squared.

$N_{\text{batch}}$ is the number of batches the simulation was divided, each containing 10000 particles. Convention is that minimum number of batches is 10.
The eMC algorithm stops the simulation when the stated mean statistical accuracy is achieved or the specified number of particles is transported. The time required to complete the eMC calculation increases as the inverse square of the specified accuracy. It should be noted that according to Zankovski et al [2], the point-to-point variance in dose values may exceed the mean statistical accuracy defined for the calculation.

The Maximum number of particle histories specifies the maximum number of particles to be transported in calculation. The calculation stops once set number of particle have been transported even if desired Accuracy is not reached. If value for particle histories is set to zero transport will last until required Accuracy is reached. In our study we discovered that if 100 000 000 particles are used in simulation (this is the maximum value accepted from Eclipse™) relative uncertainty of the mean dose reported from Eclipse ranged from 0.32% to 0.57%, depending on energy, grid size, and field size used in the simulation.

The Random number seed generator is used to define the starting point of each simulation. The Monte Carlo calculations are dependent on the exact sequence in which random number are generated. If different random number seeds are used in eMC simulations, results will be slightly different (within the defined level of accuracy).

The Smoothing method, is also referred as denoising, is used in eMC to filter out the statistical noise in the final dose distribution. There are three possible options: first is No smoothing in this case dose distribution is not altered, second one is 2-D Median applies a median filter to the dose distribution on each CT slice and last one is 3-D Gaussian which convolves the dose distribution with a 3 dimensional Gaussian with the standard deviation defined by the Smoothing level. Smoothing affects the high gradient areas of the dose distribution.
The **Smoothing level** defines different levels of intensity of the two existing smoothing methods (**2-D Median** and **3-D Gaussian**) users can apply. Each of the smoothing algorithms can be applied with three different intensities.

**1-Low** in the case of **2-D Median** applies a median filter to the dose distribution on each CT slice in neighbourhood with dimensions 5 x 5 mm.

**1-Low** in the case of **3-D Gaussian** the dose distribution is convolved with 3-D gaussian with standard deviation (SD) = 0.5 x **Calculation grid size** used for present simulation.

**2-Medium** in the case of **2-D Median** applies a median filter to the dose distribution on each CT slice in neighbourhood with dimensions 10 x 10 mm.

**2-Medium** in the case of **3-D Gaussian** the dose distribution is convolved with 3-D gaussian with standard deviation (SD) = **Calculation grid size** used for present simulation.

**3-Strong** in the case of **2-D Median** applies a median filter to the dose distribution on each CT slice in neighbourhood with dimensions 15 x 15 mm.

**3-Strong** in the case of **3-D Gaussian** the dose distribution is convolved with 3-D gaussian with standard deviation (SD) = 1.5 x **Calculation grid size** used for present simulation.

### 5.1.2 Dosimetric data requirements

In order to perform the configuration of the electron Monte Carlo (eMC) algorithm depth dose curves and profiles must be measured and fitted to pre-calculated data. The configuration requires beam data measurements for the full open field beam and energy/applicator combinations.
5.1.2.1 Open field data

The full open-field measurements should be provided for each electron energy (6, 9, 12, 16, 20 MeV). These measurements were done without presence of the applicator, with collimator jaws fully opened (40 x 40 cm²). The following open-field depth dose measurements in water must be provided for Eclipse™ configuration:

- Percent-depth-dose curve (PDD) in water phantom at the Source-to-Surface Distance (SSD) = 100 cm for each electron energy.
- Output of the Linac (Absolute dose) to water, at a specified point on the depth dose curve (usually $d_{\text{max}}$ or point close to it) expressed in [cGy/MU] for each electron energy.
- The profile in air at Source-to-Detector Distance (SDD) = 95 cm. The acquired signal is normalized to 1 on the beam axis.

A specified point on the depth dose curve, used for Beam configuration, corresponds to the Calibration depth and absolute dose in water at this point corresponds to the Calibration factor.

5.1.2.2 Applicator data

Percent depth dose measurements in water at SSD = 100 cm must be performed for each energy (6, 9, 12, 16, 20 MeV)/applicator (6 x 6, 10 x 10, 15 x 15, 20 x 20, 25 x 25 cm²) combination with standard cutout inserts.

In addition, absolute dose to water in [cGy/MU], at a specified point on the depth dose curve ($d_{\text{max}}$ or point close to it) is required by the TPS for each applicator.
It should be noted that the first point of all depth dose curve data must be at a depth of 0.5 mm or shallower. In our case the surface dose was extrapolated from measurement.

Another requirement with is that the absolute dose (in cGy/MU) of an applicator for the particular energy must be greater than or equal to the absolute dose of an open-field for the same energy.

A *Calibration factor* for each electron energy is required to relate the absolute dose to the particle fluence, or the total number of particle histories used in simulation. Therefore, results of Eclipse™ calculations are expressed in absolute dose. Monitor units (MU) are calculated from $d_{\text{max}}$ and a system *Calibration factor*. However, since Monte Carlo simulations are statistically noisy, eMC calibrates the MU against the mean value of voxels receiving greater than 99% of $d_{\text{max}}$ [2].

### 5.2 Beam data measurements

The electron Monte Carlo (eMC) algorithm is configured using measured depth dose curves and profiles. The measuring device employed in these measurements was the waterproof ion chamber (IC-10, Wellhöfer, Dosimetrie) and 3D water tank (WP700, Wellhöfer, Schwarzenbruck, Germany). The scanning distance, for depth dose measurements, was set to be at 1 mm intervals at SSD=100 cm.

For profiles in air the setup was slightly changed. The measuring ion chamber was placed at Source-to-Detector-Distance (SDD) SDD=95 cm and as far as possible from any surface to diminish the backscattered radiation signal. The ion chamber was scanned perpendicularly to the electron beam. The scanning distance was set to be at 5 mm intervals.

According to TG-25 [3], the effective point of measurement of a cylindrical ion chamber should be the distance equal to half of the radius between measuring
electrodes upstream for all energies and depths. Since the radius of the IC-10 is 3 mm, the point of measurement was shifted 1.5 mm towards the source from the center of the chamber. Initially all data were collected as ionization readings and after that converted to dose by multiplying raw ionization readings by corresponding stopping power values for the specific depth and energy. Values for stopping power ratios are calculated from Burns [4] formula 4.1.

$$\left( \frac{L}{\rho} \right)^{water}_{air}(z, R_{50}) = \frac{a + b(ln R_{50}) + c(ln R_{50})^2 + d(z/R_{50})}{1 + e(ln R_{50}) + f(ln R_{50})^2 + g(ln R_{50})^3 + h(z/R_{50})}$$ (5.3)

Where $a = 1.0752$, $b = -0.508767$, $c = 0.08867$, $d = -0.08402$, $e = -0.42806$, $f = 0.064627$, $g = 0.003085$ and $h = -0.12460$, $R_{50}$ and $z$ are expressed in cm. $R_{50}$ was calculated according to TG-51 protocol [5] from equations 5.3

$$R_{50} = 1.029 \times I_{50} - 0.06 \text{ cm} \quad (if \ 2 < I_{50} < 10 \text{ cm})$$

$$R_{50} = 1.059 \times I_{50} - 0.37 \text{ cm} \quad (if \ I_{50} > 10 \text{ cm})$$ (5.4)

Where $I_{50}$ – is the depth in an electron beam at which ionization curve falls to 50% of its maximum. $I_{50}$ is expressed in cm.

5.3 Validation measurements

5.3.1 PDD’s and Profiles

Most of the PDD’s and all of the profiles of the validation measurements were measured using a p-Si diode (Scanditronix, Uppsala, Sweden) scanned through a 49x49x49 cm$^3$ water tank Radiation Field Analyzer -300 (RFA-300) (Scanditronix, Uppsala, Sweden). For depth dose measurements, the measuring p-Si diode was positioned vertically along the central axis in water. A second, reference p-Si diode was placed on the applicator inside the irradiated field to
compensate for fluctuation in output of the Linac. The scanning interval, for depth
dose measurements was set to 0.2 mm for 6 MeV electron beam and 0.5 mm for
the other electron beam energies. According to manufacturer specification, the
effective point of measurements is displaced from the detector front surface 0.55
mm. Some of the diode PDD measurements were compared with Roos type
parallel-plate ion chamber PPC40 measurements. Since the front window
thickness of PPC40 is 1 mm, the point of measurement must be shifted 1 mm
away from the radiation source and depth ionization data collected from chamber
were converted to depth dose data as described in section 5.2.

The setup for measuring profiles was same as for the depth dose measurement
except the diode was scanned perpendicularly to the electron beam. Profiles
were obtained at 3 different depths for each field size: \( d_{\text{max}} \), \( d_{90} \) and \( d_{50} \). The
depths were determined from PDD curve measured previously. Also, profiles
were taken in the in-plane and cross-plane directions.

For the extended SSD measurements the p-Si diode was used, as well. Distance
from the source was increased to SSD=110 cm and only one applicator (10x10
cm\(^2\)) with cutout insert 10x10 cm\(^2\) was measured for all available energies.

### 5.3.2 Relative Output Factors (ROF)

According to TG-25 [3] relative output factor (ROF), is defined as the ratio of the
maximum central-axis dose for a given energy, field size and SSD, per monitor
unit, over the maximum central-axis dose for the reference 10x10 cm\(^2\) field at
SSD=100 cm, per monitor unit, for this energy.

\[
ROF(E, A, SSD) = \frac{D_{\text{MAX}}(E, A, SSD)}{D_{\text{MAX}}(E, 10x10 \text{ cm}^2, SSD = 100 \text{ cm})} \quad (5.5)
\]
The relative output factors in this study were measured with Markus Advanced chamber by placing it at the specific $d_{\text{max}}$ previously determined from PDDs curve for the field size under investigation and particular energy. Since the front window thickness of Markus Advanced is 1 mm, to obtain readings at $d_{\text{max}}$ the point of measurements was shifted 1 mm towards the radiation source. RFA-300 3D water tank was used to position Markus Advanced chamber at the required depth and chamber was connected to the Keithley 6517A electrometer. The electrometer was operated in Coulomb charge mode with voltage applied to the chamber (+300 V). In this type of measurement, prior irradiation it is necessary to condition the chamber. Our warm up procedure involved pre-irradiating the chamber with approximately to about 6 Gy. The fact that Markus Advanced chamber has a small measuring volume of 0.02 cm$^3$ and the collector electrode element 5 mm in diameter, results in adequate spatial resolution [6] for these ROF measurements. To measure Relative Output Factors (ROF) with this particular chamber 500 MU were delivered per measurement in order to obtain reasonable amount of charge accumulated. The charge accumulated at $d_{\text{max}}$ for 500 MU of irradiation was multiplied by the stopping power ratio at that depth and energy.

5.3.3 EBT GafChromic® film measurements – SSD=110 cm oblique incidence

In order to perform to perform 2D measurements with EBT GafChromic® film, it is essential that the protocol previously described in chapter 4.3.1 is strictly followed. The irradiation of the films sheets was done under the following conditions. Film was sandwiched in between two slabs of solid water and taped to the bottom edges to avoid displacement of the film from the desired position for the measurements. These two slabs were carefully placed in the middle of the solid
water phantom with dimensions 30 x 30 x 25 cm³ and were squeezed with a clamp to prevent air pockets in between slabs or film sheet used for measurement. The phantom was positioned in such a way that film sheet was parallel to the electron beam. Measurements were performed with the 9 MeV and 10x10 cm² cutout insert in the 10x10 cm² applicator.

The gantry of the Linac was positioned in four different angles (10°, 20°, 30°, 45°) above the phantom surface at source-to-surface distance (SSD) SSD = 110 cm.

References:

Chapter 6: Results and Discussion

6.1 Validation of the MC model for standard clinical data

6.1.1 PDD’s comparison

Illustrated in Figure 6.1 (A) are central axis PDD curves for all energies for the 10x10 cm² applicator. Figure 6.1 (B) is a graph of percentage difference as a function of depth between measured data and Eclipse™ calculated data. We observe from this graph the increased discrepancy in the build up region for each beam due to the “noisy” nature of the Monte Carlo calculation at these depths. Past $d_{\text{max}}$, through the therapeutic range down to $R_{50}$, the discrepancy between the data is less than 1%. In fact, for this particular example agreement between Eclipse™ simulated data and measurements are very good.

To establish a single quantative parameter to evaluate the PDD results, we define the mean difference as:

$$
\Delta D_M = \frac{1}{N} \sum_i \text{abs} (\Delta D_i) \quad (6.1)
$$

Where,

$N$ – is the number of the points taken into account up to $R_{50}$.

$\Delta D_i$ – is the difference between measured dose and Eclipse™ simulated dose at certain depths in percents.

The first depth of calculation for the PDD curves depends on the grid size chosen for simulation. For 6 and 9 MeV electron energies all calculation where done with 1 mm grid size, for 12 MeV grids was set to be 2 mm and for 16 and 20 MeV was 2.5 mm. We note that points simulated near the surface was suffer from interface effects and
Results and Discussion

A large discrepancy appears between measured and simulated data within the first layer of voxels closest to the surface of the phantom. These problems arise from the inadequate extrapolation of data near the surface by the model.

A)

![Electron PDD cone 10x10 cm²](image)

B)

![10x 10 cm² All Energies](image)

Figure 6.1: A) Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 10 x 10 cm² applicator. (--) – Solid line for measured data with PPC 40, (o) – Eclipse™ simulated data. B) Variation in the corresponding Percent Depth Dose difference up to depth of R₅₀.
For this reason the first point of comparison was taken at depths based on the calculation grid size. Table 6.1 summarizes the $\Delta D_M$ for all above mentioned energies and applicators. Form the Table 6.1 we can clearly see that with increasing energy we obtain better agreement between measurements and calculation. In terms of $\Delta D_M$, for this particular experiment, all values lie below 3%, and in fact, aside from 6 MeV beam, and a solitary instance for the 12 MeV (25 x 25 cm$^2$) beam all results are better than 2%.

<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
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<tr>
<td>6 x 6</td>
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<td>1.03</td>
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<td>0.81</td>
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<td>10 x 10</td>
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<td>1.02</td>
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<td>0.71</td>
</tr>
<tr>
<td>15 x 15</td>
<td>2.88</td>
<td>1.11</td>
<td>1.64</td>
<td>0.54</td>
<td>0.62</td>
</tr>
<tr>
<td>20 x 20</td>
<td>2.89</td>
<td>1.40</td>
<td>1.58</td>
<td>1.67</td>
<td>1.62</td>
</tr>
<tr>
<td>25 x 25</td>
<td>2.56</td>
<td>1.35</td>
<td>2.89</td>
<td>0.75</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 6.1: $\Delta D_M$ between measured central-axis percentage depth dose curves for all standard applicators.

Shown in Figure 6.2 to 6.6 are the PDD curves for each available energy for all standard applicators, comparing measured data to Eclipse™ simulated data. We note from several of the graphs that we have good agreement between measured and Eclipse™ data. However, there exist certain discrepancies. For the 6 MeV beam these discrepancies are noted in the build up region up to 6.4% difference with distance-to-agreement (DTA) = 2.5 mm and in the region between $R_{50}$ and $R_p$ up to differences of 6.8% with DTA=1 mm. For the 9 MeV beam these discrepancies are observed in the region between $R_{90}$ and $R_{80}$ (up to 4.8% with DTA=1.5 mm) and in the region between $R_{50}$ and $R_p$ (up to 5% with DTA=1.5 mm). For the 12 MeV beam
Eclipse™ under estimates the dose in the build up region (up to 5.5% with DTA= 3 mm). The 16 MeV beam has the best agreement between measured and simulated data with noted discrepancies not exceeding 3%. For the highest available energy, 20 MeV, beam differences are observed in the region between $R_{50}$ and $R_p$ (up to 4.5% with DTA=2.5 mm). For all investigated energies there are no differences between calculated and measured data on the PDD curves exceeding Van Dyk criteria of 4 mm DTA. There appears to be no particular trend in the data, except that the 6 MeV beam has the worst agreement and the 16 MeV best. Considering that the most important part of the PDD for the patient prescription and planning is between $d_{max}$ and the $R_{90}$ or $R_{80}$, and that error in the high dose gradient area, an tail of the curves the DTA is within a couple of mm. This particular set of data would be adequate for clinical use.
Figure 6.2: Central-axis depth dose distributions for 6 MeV electron beam energy with 6 x 6 cm², 10 x 10 cm², 15 x 15 cm², 20 x 20 cm² and 25 x 25 cm² applicators. (--) - Solid line for measured data with p-Si diode, (a) – Eclipse™ simulated data.
Figure 6.3: Central-axis depth dose distributions for 9 MeV electron beam energy with 6 x 6 cm², 10 x 10 cm², 15 x 15 cm², 20 x 20 cm² and 25 x 25 cm² applicators. (--) - Solid line for measured data with p-Si diode, (o) – Eclipse™ simulated data.
Figure 6.4: Central-axis depth dose distributions for 12 MeV electron beam energy with 6 x 6 cm$^2$, 10 x 10 cm$^2$, 15 x 15 cm$^2$, 20 x 20 cm$^2$ and 25 x 25 cm$^2$ applicators. (--) - Solid line for measured data with p-Si diode, (o) – Eclipse™ simulated data.
Results and Discussion

Figure 6.5: Central-axis depth dose distributions for 16 MeV electron beam energy with 6 x 6 cm², 10 x 10 cm², 15 x 15 cm², 20 x 20 cm² and 25 x 25 cm² applicators. (--) - Solid line for measured data with p-Si diode, (•) – Eclipse™ simulated data.
Figure 6.6: Central-axis depth dose distributions for 20 MeV electron beam energy with 6 x 6 cm², 10 x 10 cm², 15 x 15 cm², 20 x 20 cm² and 25 x 25 cm² applicators. (--) - Solid line for measured data with p-Si diode, (a) – Eclipse™ simulated data.
6.1.2 Table of parameters

In Table 6.2 are presented the results obtained from Eclipse™ simulated dose distributions and data measured with PPC 40 ion chamber for electron beam planning parameters. For the energies of 6 and 9 MeV Eclipse™ tends to underestimate the depth of maximum dose by 1 mm, and for 12 MeV overestimates it by 1 mm. For the three above mentioned energies the TPS overestimates the practical range by 1 mm. For the rest of the parameters $R_{90}$, $R_{80}$ and $R_{50}$, the discrepancies among simulated and measured data were within 1 mm. For the highest two available energies 16 and 20 MeV difference in $d_{\text{max}}$ is 2 mm due to a broader $d_{\text{max}}$ region for these energies. The actual dose difference is less than 1% at the depth of maximum dose. From the Table 6.2 and the PDDs shown in Figures 6.2 to 6.6 we see a trend for Eclipse to overestimate the $R_p$ for the lower energies, this trend is reversed for the higher energies, and for 20 MeV, Eclipse™ underestimates the $R_p$ by 1 mm. For all energies there is no beam planning parameter which has a distance-to-agreement greater than 2 mm.
### Electron beam planning parameters

#### Clinac 21 EX - Electrons

<table>
<thead>
<tr>
<th>Treatment parameter</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>E**</td>
<td>M</td>
<td>E</td>
<td>M</td>
</tr>
<tr>
<td>dmax (mm)</td>
<td>13.0</td>
<td>12.0</td>
<td>21.0</td>
<td>20.0</td>
<td>28.0</td>
</tr>
<tr>
<td>R_{90} (mm)</td>
<td>18.0</td>
<td>18.0</td>
<td>27.5</td>
<td>27.5</td>
<td>38.5</td>
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<tr>
<td>R_{50} (mm)</td>
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<td>20.0</td>
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<td>30.0</td>
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<tr>
<td>R_{p} (mm)</td>
<td>24.0</td>
<td>24.0</td>
<td>36.0</td>
<td>36.5</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Table 6.2: Table of electron beam planning parameters for 6, 9, 12, 16, and 20 MeV electron energies, simulated by Eclipse™ and measured with PPC 40 ion chamber.

M* - stands for Measured data, E** - stands for Eclipse™ simulated data.
6.1.3 Table of Relative Output Factors (ROF)

The Relative Output factors are shown in Table 6.4 which comprises measured values and Eclipse™ simulated values for applicators with standard dimensions.

The difference is defined as:

\[
\text{%diff} = \left| \frac{\text{Measured} - \text{Eclipse simulated}}{\text{Measured}} \right| \times 100
\]  

(6.2)

<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% diff</td>
<td>% diff</td>
<td>% diff</td>
<td>% diff</td>
<td>% diff</td>
</tr>
<tr>
<td>6 x 6</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>10 x 10</td>
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<td>0.2</td>
<td>0.5</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>15 x 15</td>
<td>0.5</td>
<td>0.4</td>
<td>0.8</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>20 x 20</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>25 x 25</td>
<td>0.1</td>
<td>0.2</td>
<td>1.3</td>
<td>0.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 6.3: Percent difference between ROF measured for standard cutout inserts and Eclipse™ simulate one for all available energies on a CL 21 EX.

From Table 6.3 we note that for most of the cutouts the discrepancy is less than 1%. There are only four values exceeding 1% with a maximum of a 1.9% for the (25 x 25 cm²) applicator and 20 MeV electron beam energy. In order to diminish that difference and to obtain better agreement between measured and simulated data the Calibration factor value for particular cutout and energy can be manipulated in TPS. Based on these results, we propose that the Eclipse™ system could be used clinically in the context of ROF and monitor unit calculations for this standard applicator set and all energies.
### Table 6.4: Table of the Relative Output Factors for 6, 9, 12, 16, and 20 MeV electron energies, measured and simulated by Eclipse™.

<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M*</td>
<td>E**</td>
<td>%diff</td>
<td>M</td>
<td>E</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td>95.9</td>
<td>96.6</td>
<td>0.7</td>
<td>97.3</td>
<td>97.0</td>
</tr>
<tr>
<td>10 x 10</td>
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<td>100.2</td>
<td>0.2</td>
<td>100.0</td>
<td>99.8</td>
</tr>
<tr>
<td>15 x 15</td>
<td></td>
<td>100.2</td>
<td>99.7</td>
<td>0.5</td>
<td>99.9</td>
<td>99.5</td>
</tr>
<tr>
<td>20 x 20</td>
<td></td>
<td>101.3</td>
<td>101.5</td>
<td>0.2</td>
<td>98.6</td>
<td>98.8</td>
</tr>
<tr>
<td>25 x 25</td>
<td></td>
<td>100.7</td>
<td>100.8</td>
<td>0.1</td>
<td>96.4</td>
<td>96.6</td>
</tr>
</tbody>
</table>

M* - stands for Measured data, E** - stands for Eclipse™ simulated data.
6.1.4 Profiles

Shown in Figure 6.7 are the profiles (measured vs Eclipse™) for all energies and the 10 x10 cm² applicator at depths of \(d_{\text{max}}\), \(R_{90}\) and \(R_{50}\). Once again there is good agreement (between \(\pm 3\%\), or \(\pm 2\%\) if PDD discrepancies accounted for) between measured and calculated data in all cases. Some discrepancies were found for the 20 MeV electron beam at depth of the maximum dose in umbra region. Eclipse™ underestimates the dose by maximum of 3.3\%. Since, this discrepancy appears in small dose gradients in the low dose region (it is <7\% of the normalization dose), this does not exceeds recommendation of Van Dyk [1] for acceptability.

For the 20 MeV electron beam (Figure 6.8) all clinically available standard cutouts were simulated and the profiles were compared with measurements at depth of maximum dose, \(R_{90}\) and \(R_{50}\). For the 20 x 20 cm² applicator in central portion of the profile and in shoulder, Eclipse™ underestimates the dose by about 4.5\% and the discrepancy appears in depths of \(R_{90}\) and \(R_{50}\) reaches its maximum value at depth of \(R_{50}\). The observed discrepancy is a direct result of difference in PDD curves (measured and Eclipse™ calculated) for this particular cutout/energy combination (see Figure 6.6). Improvement could be achieved by slight modification of the Calibration Factors for this applicator. For the rest of applicators calculated profiles are in excellent agreement with measurements.
Figure 6.7: Profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for $10 \times 10 \text{ cm}^2$ for 6, 9, 12, 16 and 20 MeV electron beams. (--) – Solid line measured by the p-Si diode, (Δ) – Eclipse™ simulated.
Figure 6.8: Profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for 20 MeV electron beam modified with $6 \times 6 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$, $15 \times 15 \text{ cm}^2$, $20 \times 20 \text{ cm}^2$ and $25 \times 25 \text{ cm}^2$ cutout inserts. (--) – Solid line measured by the p-Si diode, (Δ) – Eclipse™ simulated.
6.2 Validation of MC model for irregularly shaped cutouts.

6.2.1 PDD comparison

The percentage depth dose curves simulated by the Eclipse™ are in good agreement with the measurements with an average $\Delta D_M$ 2.38% (see Table 6.5) and distance-to-agreement of 2 mm for all irregular cutouts investigated in this study. The Figures 6.9 to 6.15 represent the results obtained for all thirteen irregular cutouts with 6, 9, 12, 16 and 20 MeV electron beam energies. For the 6 MeV electron beam energy Eclipse™ simulated data and measured data have a lower level of agreement. A maximum value of 4.97% $\Delta D_M$ and distance-to-agreement of 2.5 mm was obtained for the cutout with dimensions $10 \times 1 \text{ cm}^2$. The 9 and 12 MeV beams also reached the highest values for $\Delta D_M$ for this cutout, 2.38% and 2.12%, respectively. From the results obtained in our study we can conclude that Eclipse™ calculated depth dose distributions have a lower level of agreement with measured data for small fields for all studied energies.

Additionally, it appears that the agreement is also poorer when considering the long narrow fields ($10 \times 1 \text{ cm}^2$ etc.). These discrepancies may be indicative of problems encountered with the measurement of small electron fields. Generally however, the agreement is excellent, and we consider that under similar conditions, with custom cutouts the Eclipse™ could be used clinically.
<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
<td>$\Delta D_M$ (%)</td>
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</tr>
<tr>
<td>8 x 5</td>
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<td>0.63</td>
</tr>
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</tr>
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</tr>
<tr>
<td>8 x 2</td>
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</tr>
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<td>10 x 1</td>
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<td>0.74</td>
</tr>
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<td>D 5</td>
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<td>1.46</td>
<td>0.62</td>
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<td>D 4</td>
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<td>0.99</td>
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<td>0.76</td>
</tr>
<tr>
<td>D 3</td>
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<td>0.89</td>
<td>0.58</td>
<td>0.60</td>
</tr>
<tr>
<td>D 2</td>
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<td>2.45</td>
<td>1.54</td>
<td>1.24</td>
<td>0.84</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 6.5: $\Delta D_M$ in percents between measured central-axis percentage depth dose curves for all irregular cutout inserts and Eclipse™ simulate one for 6, 9, 12, 16 and 20 MeV electron beam energies.
Figure 6.9: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 8 x 5 cm² and 8 x 4 cm² cutout inserts. (--) – Solid line for measured data with p-Si diode, (○) – Eclipse™ simulated data.
Figure 6.10: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 8 x 3 cm$^2$ and 8 x 2 cm$^2$ cutout inserts. (--) – Solid line for measured data with p-Si diode, (○) – Eclipse™ simulated data.
Figure 6.11: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 10 x 1 cm$^2$ and 5 cm Diameter cutout inserts. (---) – Solid line for measured data with p-Si diode, (○) – Eclipse™ simulated data.
Figure 6.12: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 4 cm Diameter and 3 cm Diameter cutout inserts. (--) - Solid line for measured data with p-Si diode, (•••) - Eclipse™ simulated data.
Figure 6.13: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 2 cm Diameter and 1 cm Diameter cutout inserts. (--) – Solid line for measured data with p-Si diode, (©) – Eclipse™ simulated data.
Figure 6.14: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with and cutout inserts. (--) – Solid line for measured data with p-Si diode, (○) – Eclipse™ simulated data.
Figure 6.15: Depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 0 cutout insert. (---) – Solid line for measured data with p-Si diode, (o) – Eclipse™ simulated data.
6.2.2 Table of Relative Output Factors (ROF)

Thirteen irregularly shaped cutouts were simulated and measured; some of them intentionally designed with small dimensions and extremities in order to determine the limits of the eMC model in Eclipse™. The values obtained from Eclipse™ calculations and results from measurements of the ROF are shown in Table 6.6. The measured and simulated Relative Output factors coincide to within 2.7% for field sizes or diameter larger than 2 cm. For field sizes with diameter 2 cm and less (10x1 cm² and 8x2 cm²) the discrepancy between measured and simulated results reached maximum value of 19.6%. Since, ROF’s were measured with a Marcus Advanced ion chamber with a 5 mm collecting electrode, the observed difference between measured and simulated data can not be completely attributed to the Eclipse™ model limitations. The lack of lateral charge particle equilibrium at the depth of the maximum dose can significantly affect the measurements. For very small field sizes, a smaller detector with higher spatial resolution must be employed. Overall however, the results are excellent. If we exclude the discrepancies found for 10 x 1 cm² and the 1 cm diameter cutouts exceeding Van Dyk criteria, all differences are less than 3% and, of those only 2 are greater than 2%.

6.2.3 Depth of maximum dose on central axis.

The Table 6.7 summarizes the results for $d_{\text{max}}$ obtained by Eclipse™ simulations and by p-Si diode measurements for various field sizes, shapes and all energies. The agreement between measured and Eclipse™ calculated $d_{\text{max}}$ match within 2.5 mm for the 6 MeV electron beam and within 2.0 mm for the 9 MeV electron beam. For 12, 16 and 20 MeV electron beams they coincide within 4.0 mm, 5.5 mm and 4.5 mm, respectively. It should be mentioned that for 6 MeV electron beam the Eclipse™ simulated $d_{\text{max}}$ for all investigated irregular cutouts was on average 1.0 mm closer to the surface compared to the measured ones. This is probably due to the shifting of PDD curves at the time of beam data entry to improve match between measured
and simulated data up to the level of $R_{50}$. For rest of the evaluated energies there is no pronounced trend in $d_{\text{max}}$ prediction. As expected, a higher level of discrepancy for the 12, 16 and 20 MeV electron beams appears, and this is based on broader region of $d_{\text{max}}$ for these energies. We note that while these discrepancies seem large in terms of depth, the actual difference in dose at the points where $d_{\text{max}}$ appears is less then 1% for these energies.
<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>E**</td>
<td>%diff</td>
<td>M</td>
<td>E</td>
</tr>
<tr>
<td>8 x 5</td>
<td>100.4</td>
<td>98.7</td>
<td>1.7</td>
<td>99.9</td>
<td>98.8</td>
</tr>
<tr>
<td>8 x 4</td>
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<td>98.5</td>
<td>98.0</td>
</tr>
<tr>
<td>8 x 3</td>
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<td>96.4</td>
<td>-0.9</td>
<td>93.5</td>
<td>94.7</td>
</tr>
<tr>
<td>8 x 2</td>
<td>85.6</td>
<td>92.7</td>
<td>-8.3</td>
<td>87.7</td>
<td>92.2</td>
</tr>
<tr>
<td>10 x 1</td>
<td>64.4</td>
<td>77.0</td>
<td>-19.6</td>
<td>74.3</td>
<td>82.9</td>
</tr>
<tr>
<td>D 5</td>
<td>100.2</td>
<td>98.6</td>
<td>1.6</td>
<td>98.6</td>
<td>97.2</td>
</tr>
<tr>
<td>D 4</td>
<td>94.0</td>
<td>93.0</td>
<td>1.1</td>
<td>93.6</td>
<td>92.0</td>
</tr>
<tr>
<td>D 3</td>
<td>86.8</td>
<td>87.0</td>
<td>-0.2</td>
<td>89.0</td>
<td>88.9</td>
</tr>
<tr>
<td>D 2</td>
<td>74.4</td>
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<td>-6.2</td>
<td>83.1</td>
<td>85.0</td>
</tr>
<tr>
<td>D 1</td>
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<td>-10.7</td>
<td>60.2</td>
<td>64.4</td>
</tr>
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<td>97.2</td>
<td>96.6</td>
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<td>95.7</td>
<td>95.9</td>
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<td>93.4</td>
</tr>
<tr>
<td></td>
<td>92.9</td>
<td>93.6</td>
<td>-0.8</td>
<td>92.7</td>
<td>93.9</td>
</tr>
</tbody>
</table>

Table 6.6: Table of the Relative Output Factors for 6, 9, 12, 16, and 20 MeV electron energies, for thirteen irregularly shaped cutouts, measured and simulated by Eclipse™.

M* - stands for Measured data, E** - stands for Eclipse™ simulated data.
<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>E**</td>
<td>diff</td>
<td>M</td>
<td>E</td>
</tr>
<tr>
<td>8 x 5</td>
<td>13.5</td>
<td>12.5</td>
<td>-1.0</td>
<td>20.5</td>
<td>20.5</td>
</tr>
<tr>
<td>8 x 4</td>
<td>13.5</td>
<td>12.5</td>
<td>-1.0</td>
<td>20.5</td>
<td>20.5</td>
</tr>
<tr>
<td>8 x 3</td>
<td>13.5</td>
<td>12.5</td>
<td>-1.0</td>
<td>20.5</td>
<td>19.5</td>
</tr>
<tr>
<td>8 x 2</td>
<td>11.5</td>
<td>9.0</td>
<td>-2.5</td>
<td>13.5</td>
<td>15.5</td>
</tr>
<tr>
<td>10 x 1</td>
<td>6.0</td>
<td>5.5</td>
<td>-0.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>D 5</td>
<td>14.5</td>
<td>12.5</td>
<td>-2.0</td>
<td>22.0</td>
<td>20.0</td>
</tr>
<tr>
<td>D 4</td>
<td>14.0</td>
<td>12.5</td>
<td>-1.5</td>
<td>20.0</td>
<td>20.5</td>
</tr>
<tr>
<td>D 3</td>
<td>13.0</td>
<td>12.5</td>
<td>-0.5</td>
<td>16.0</td>
<td>15.5</td>
</tr>
<tr>
<td>D 2</td>
<td>9.0</td>
<td>8.5</td>
<td>-0.5</td>
<td>9.0</td>
<td>10.0</td>
</tr>
<tr>
<td>D 1</td>
<td>2.5</td>
<td>1.0</td>
<td>-1.5</td>
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<td>5.5</td>
</tr>
<tr>
<td>D 05</td>
<td>13.0</td>
<td>12.5</td>
<td>-0.5</td>
<td>19.5</td>
<td>19.0</td>
</tr>
<tr>
<td>D 04</td>
<td>14.0</td>
<td>12.5</td>
<td>-1.5</td>
<td>19.5</td>
<td>17.5</td>
</tr>
<tr>
<td>D 03</td>
<td>13.5</td>
<td>12.5</td>
<td>-1.0</td>
<td>18.0</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 6.7: Depths of maximum dose for 6, 9, 12, 16, and 20 MeV electron energies, for thirteen irregularly shaped cutouts, measured values and simulated by Eclipse™.

M* - stands for Measured depths in [mm], E** - stands for Eclipse™ simulated depths in [mm].
6.2.4 Profiles

Several examples of dose profiles are shown on Figures 6.16 and 6.17. Profiles calculated by the Eclipse™ are in good agreement with measured dose profiles. A large discrepancy is obtained for Eclipse™ simulated profiles in the sagittal plane in the shoulder of the profiles and in penumbra areas at depth of maximum dose and $R_{90}$. This effect is in fact an artifact obtained when using digital phantom for calculation. The TPS calculates dose on each transversal plane slice and interpolates values in between for sagittal planes. The penumbra region in this case lies between slices. The problem can be resolved by producing a higher resolution (slice thickness and separation) data set for calculation as is done for patients and other imported CT scans. In general the calculated profiles are in excellent agreement with measurement. Aside from the problems mentioned for the sagittal planes, the doses are with in ±3% in the plateau regions and the DTA is less than 2 mm in the penumbra regions.
Figure 6.16: Examples of profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for 12 MeV electron beams transversal and sagittal planes. (--) – Solid line measured by the p-Si diode, ($\Delta$) – Eclipse™ simulated.
Results and Discussion

Figure 6.17: Profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for 3 cm diameter cutout insert for 6, 9, 12, 16 and 20 MeV electron beams at SSD = 100 cm. (--) – Solid line measured by the p-Si diode, (Δ) – Eclipse™ simulated.
6.3 Extended SSD = 110 cm

Further evaluation of the Eclipse™ was performed by increasing SSD from 100 cm to 110 cm. Measurements and simulations were performed for 6, 9, 12, 16 and 20 MeV electron beams modified with a standard 10 x 10 cm² cutout.

<table>
<thead>
<tr>
<th>Cutout size (cm x cm)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔDₘ (%)</td>
<td>ΔDₘ (%)</td>
<td>ΔDₘ (%)</td>
<td>ΔDₘ (%)</td>
<td>ΔDₘ (%)</td>
</tr>
<tr>
<td>10 x 10</td>
<td>3.27</td>
<td>1.90</td>
<td>2.12</td>
<td>0.89</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 6.8: ΔDₘ between measured central-axis percentage depth dose curves for 10 x 10 cm² standard applicator at extended SSD=110 cm.

Results for depth dose curves are shown in Figure 6.18 and the ΔDₘ is summarized in Table 6.8 for all energies. For 6, 9 and 12 MeV the agreement between measured and simulated data are not as good as they are for SSD = 100 cm. A higher discrepancy appears in the region between R₈₀ and Rₚ for these three energies reaching maximum value of 2.0 mm distance-to-agreement at the depth of Rₚ for the 6 and 9 MeV electron beams (Table 6.9). For the 16 and 20 MeV electron beams, the measured and simulated data are in excellent agreement. Even though, the difference between simulated and measured depths of the maximum dose reaches values of 4 mm and 10 mm for 16 and 20 MeV beams, respectively, it is due to the broad dₘₐₓ for these energies, and the dose difference at these depths are within 1% and the DTAs is negligible. Generally however for the over range of clinical parameters the agreement is excellent.

The profiles were calculated and measured at the depth of maximum dose, R₉₀ and R₅₀ for a 10 x 10 cm² field size for all energies. The same degree of agreement was achieved as for the central-axis depth dose, data above (Figures 6.19 and 6.20).
The shape and the width of the simulated profiles for all energies at all the above mentioned depths coincide with measured data in an excellent manner. Any discrepancies in the central axis of the dose profiles are of course, related to the discrepancy in PDD curves for each energy.

Figure 6.18: Extended SSD = 110 cm depth dose curves for 6, 9, 12, 16, and 20 MeV electron beam energies modified with 10 x 10 cm$^2$ cutout insert. (--) – Solid line for measured data with p-Si diode, (Δ) – Eclipse TM simulated data.

Figure 6.19: Profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for 10 x 10 cm$^2$ cutout insert for 6 and 9 MeV electron beams at SSD = 110 cm. (--) – Solid line measured by the p-Si diode, (Δ) – Eclipse TM simulated.
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Figure 6.20: Profiles at $d_{\text{max}}$, $R_{90}$ and $R_{50}$ for 10 x 10 cm$^2$ cutout insert for 12, 16 and 20 MeV electron beams at SSD = 110 cm. (--) – Solid line measured by the p-Si diode, (Δ) – Eclipse™ simulated.

In the range of clinical parameters, in particular the therapeutic ranges $R_{80}$ and $R_{90}$ the DTAs, for the measured conditions, are all less than 1 mm, more than adequate for clinical use.
Electron beam planning parameters SSD = 110 cm.

**Table 6.9: Table of electron beam planning parameters for 6, 9, 12, 16, and 20 MeV electron energies, at SSD = 110 cm simulated by Eclipse™ and measured with p-Si diode.**

<table>
<thead>
<tr>
<th>Treatment parameter</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>E**</td>
<td>diff</td>
<td>M</td>
<td>E</td>
</tr>
<tr>
<td>d max (mm)</td>
<td>13.0</td>
<td>13.0</td>
<td>0.0</td>
<td>22.0</td>
<td>22.5</td>
</tr>
<tr>
<td>R 90 (mm)</td>
<td>18.0</td>
<td>18.5</td>
<td>0.5</td>
<td>28.0</td>
<td>28.5</td>
</tr>
<tr>
<td>R 80 (mm)</td>
<td>20.0</td>
<td>20.5</td>
<td>0.5</td>
<td>30.5</td>
<td>31.0</td>
</tr>
<tr>
<td>R 50 (mm)</td>
<td>23.5</td>
<td>25.0</td>
<td>1.5</td>
<td>35.5</td>
<td>37.0</td>
</tr>
<tr>
<td>R p (mm)</td>
<td>30.0</td>
<td>32.0</td>
<td>2.0</td>
<td>44.0</td>
<td>46.0</td>
</tr>
</tbody>
</table>

M* - stands forMeasured depths in [mm], E** - stands for Eclipse™ simulated depths in [mm].
6.4 Oblique and extended SSD

The next test performed was the comparison of isodose lines measured with GafChromic film in solid water phantom under oblique incidence and extended SSD = 110 cm conditions. The 9 MeV electron beam modified with 10 x 10 cm² standard cutout size was set to impinge the solid water phantom under four different angles 10, 20, 30 and 45 degrees. Results comparing the measured data to Eclipse™ calculated data are shown on Figures 6.21 to 6.24.

For 10 degrees of oblique incidence (Figure 6.21) results are similar to the extended 9 MeV electron beam with no obliquity. Eclipse™ over estimates the distance for dose levels with 20% and 50% of the dose by about 2 mm at the central portion of the depth dose distribution and a perfect match is seen on the lateral sides for these isodose lines. The area surrounded by 80% and 90% isodose lines in Eclipse™ is larger and 90% isodose line is wider laterally. The shape of the measured isodose lines and calculated ones are in good agreement for this setup.

For the setup of 20 degree oblique incidence (Figure 6.22) the 20% and 50% isodose lines are in excellent agreement. There exists an of over estimation from Eclipse™ in the areas surrounded by 80% and 90 % isodose lines, in the low dose side of the distribution.

The measured and simulated isodose lines for 30 and 45 degrees of gantry rotation coincide well. Strangely, these geometries show better agreement then the isodose curves for the less oblique beam incidence.
Figure 6.21: Axial distribution of dose to solid water for 9 MeV electron beam with 10x10 cm$^2$ field at SSD = 110 cm with $10^\circ$ oblique incidence. (-) – Solid lines GafChromic film isodose lines. (---) – Dotted lines Eclipse™ simulated isodose at the level of 20%, 50%, 80%, 90% and 100%.

Figure 6.22: Axial distribution of dose to solid water for 9 MeV electron beam with 10x10 cm$^2$ field at SSD = 110 cm with $20^\circ$ oblique incidence. (-) – Solid lines GafChromic film isodose lines. (---) – Dotted lines Eclipse™ simulated isodose at the level of 20%, 50%, 80%, 90% and 100%.
Results and Discussion

Figure 6.23: Axial distribution of dose to solid water for 9 MeV electron beam with 10x10 cm\(^2\) field at SSD = 110 cm with 30\(^\circ\) oblique incidence. (-) – Solid lines GafChromic film isodose lines. (---) – Dotted lines Eclipse \(\text{TM}\) simulated isodose at the level of 20\%, 50\%, 80\%, 90\% and 100\%.

Figure 6.24: Axial distribution of dose to solid water for 9 MeV electron beam with 10x10 cm\(^2\) field at SSD = 110 cm with 45\(^\circ\) oblique incidence. (-) – Solid lines GafChromic film isodose lines. (---) – Dotted lines Eclipse \(\text{TM}\) simulated isodose at the level of 40\%, 50\%, 80\%, 90\% and 100\%. 
6.5 Comparison of the results with other authors

Several groups have reported results on the evaluation of electron beam Monte Carlo based treatment planning systems [2] [3] [4] [5]. Zankowski et al [2] published the "white paper" describing the workings and methodology behind the MC code in the Eclipse TPS, and provided comparison with EGSnrc code in a water phantom but no comparison with measured data. Only the work of Popple et al [3] compared the Eclipse TPS with measurements. These however, were performed in various phantoms for one beam geometry (15 x 15 cm²) and two beam energies (9 and 20 MeV) only. The authors found that overall they obtained an agreement of ±2.5% or DTA=2.5 mm and ±3% or DTA=3 mm between measured and calculated data for all of their measurements for 9 MeV and 20 MeV electron beams, respectively. Standard error was reported as was defined by Boyd at al [6]. For experiments performed in a water tank with a geometry similar to that used in our work, for the 9 and 20 MeV electron beams, the agreement was not explicitly reported, but the data shows similar results to ours. Reporting the standard error in same way as Popple et al did, we obtained agreement of ±2.5% or DTA=1.5 mm and ±2% or DTA<1 mm for 9 MeV and 20 MeV, respectively. Better agreement was obtained as a direct result of a higher level of accuracy employed in our simulations. Popple et al performed the simulations with 1% accuracy with no smoothing applied. We performed the simulations with maximum number of particle histories accepted by the system with no smoothing applied, resulting in an accuracy of less than 1%.

Albaret [5] compared a BEAM code to measured data for a similar set of applicators and energies as used in this work. The author reported that in general the agreement was 2.8% and DTA=1 mm up to depth of \( R_{50} \) for all energies with beam geometry 10 x10 cm². Discrepancies reported from Albaret were defined as (BEAM simulated – p-Si Measured)*100 for PDD curves. If we report the difference between measured and calculated data on the central axis depth dose curves for a similar beam geometries, our results are similar with (3.9% difference and DTA=2 mm). The
ROF factor was calculated from an in house Monte Carlo system by same author. Results reported agreed within 2.5% for all energies for fields larger than 2 cm.

Cygler et al [4] performed the evaluation of a commercial Monte Carlo electron treatment planning system THERAPLAN PLUS v.3.8 (Theratronics, Canada, ON) with embedded VMC++ Monte Carlo electron transport dose calculation code. The author evaluated only two energies, 9 MeV and 20 MeV with beam geometries 3 x 3 cm$^2$, 7 x 7 cm$^2$, and 10 x10 cm$^2$. Cygler et al reported maximum discrepancies of less than 3% or DTA=1 mm for 3 x 3 cm$^2$ field size in a build up region. For a field size with similar dimension (3 cm diameter) we obtained difference of 2.9% or DTA=1.5 mm.

References:

Chapter 7: Conclusion and future work

7.1 Summary and conclusions

The main objective of this project was to configure and validate a commercial TPS, Eclipse™, for clinical electron beams. Eclipse™ calculated dose distributions in a digital phantom were compared with measurements in homogeneous phantoms under different setups. The electron Monte Carlo (eMC) algorithm was configured for all available electron beams energies (6, 9, 12, 16, 20 MeV) on a Varian Clinac 21 EX Linac. The worst agreement between measured and calculated dose distributions were found for the 6 MeV electron beam. Measurements and calculations of depth dose curves, profiles, and Relative Output Factors (ROF) were performed for all combinations of electron beam energies and standard cutout inserts (6 x 6 cm², 10 x 10 cm², 15 x 15 cm², 20 x 20 cm², 25 x 25 cm²) at SSD=100 cm. Eclipse™ calculated dose distributions are in good agreement with measurements performed with a p-Si diode, and PPC 40, and Marcus Advanced ionization chambers. Results coincide within 2 mm distance-to-agreement for common beam planning parameters such as $R_{90}$ and $R_{80}$. For depth dose curves a 2.89% $\Delta D_M$ or 3 mm distance-to-agreement was found. A mean difference of 0.5% was found for ROF measurements. TPS has also been tested with thirteen fields with irregular shape: five circles (with diameters: 1cm, 2 cm, 3 cm, 4 cm and 5 cm), five rectangular (10x1 cm², 8x2 cm², 8x3 cm², 8x4 cm² and 8x5 cm²) and three irregular. For all non standard field sizes results form depth dose curves match to within 4.97% $\Delta D_M$ or 2.5 mm distance-to-agreement. For field sizes larger than 2 cm ROF factors coincide within 2.7% difference.

Another test was performed for normal incidence at extended SSD=110 cm with a standard field size (10x10 cm²) for all available energies. Results agree for depth
dose curves $3.27\% \Delta D_M$ or 2 mm distance-to-agreement and profiles within 2 mm DTA.

Film measurements were performed for and oblique extended SSD= (110 cm) configuration with standard (10x10 cm$^2$) cutout for a 9 MeV electron beam in a solid water phantom. A good agreement was found for those measurements, as well.

We believe that based on our results, for the geometries tested in this work, the Eclipse™ electron Monte Carlo (eMC) module could be implemented clinically for homogeneous density situations.

7.2 Future work

The next step in the Eclipse™ commissioning procedure should be evaluation of the system with phantom geometries containing density heterogeneities, and irregular surface contours, paying particular attention to doses at the tissue interfaces. It would also be interesting to verify the field matching capabilities of the system, verifying photon-electron, and electron-electron field matches for clinical conditions.

A more rigorous statistical analysis should be performed to more clearly identify some of the discrepancies found, are due to difficulties in the MC model or measurement technique.
Bibliography:


Mackie, T.R., "Applications of the Monte Carlo method in radiotherapy".


