VERIFICATION OF THE RULE OF THUMB TO DETERMINE ELECTRON RANGE PARAMETER USING EGSNRC MONTE CARLO

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by

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of requirements for the degree of
Bachelor of Medical Radiation (Honours)

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CERTIFICATE

This is to certify that the dissertation entitled "Verification of the Rule of Thumb to Determine Electron Range Parameter Using EGSnrc Monte Carlo" is the bona fide record of research work done by Ms Nur Iffah Husna Binti Aisa during the period from October 2024 to July 2025 under my supervision. I have read this dissertation and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Medical Radiation (Honours).

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated and duly acknowledged. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at Universiti Sains Malaysia or other institutions. I grant Universiti Sains Malaysia the right to use the dissertation for teaching, research and promotional purposes.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
BEAMnrc	BEAM Data Processing
CM	Component Module
DOSXYZnrc	DOSXYZ National Research Council
ECUT	Electron cut-off Energy
EGSnrc	Electron Gamma Shower National Research Council
EPOM	Energy-dependent effective point of measurement
GUI	Graphical User Interface
HPUSM	Hospital Pakar Universiti Sains Malaysia
IAEA	International Atomic Energy Agency
IC	Ionisation Chamber
ICRU	International Commission on Radiation Units and Measurements.
LINAC	Linear Accelerator
MC	Monte Carlo
MU	Monitor Unit
PCUT	Photon cut-off Energy
PDD	Percentage Depth Dose
QA	Quality Assurance
SAD	Source-to-Axis Distance
SSD	Source-to-Surface Distance
TPS	Treatment Planning System

UHDR	Ultra-High Dose Rate
USM	Universiti Sains Malaysia

LIST OF SYMBOLS

cm	Centimetre
Dd	Dose at a Certain Depth
Dmax	Dose Maximum
R_{100}	Depth at Maximum Dose
R_{50}	Depth at 50% Dose (Beam Quality)
R_{90}	Depth at 90% Dose
Rp	Practical Range
Zmax	Depth of Dose Maximum

PENGESAHAN KAEDAH ANGGARAN UNTUK MENENTUKAN PARAMETER JULAT ELEKTRON MENGGUNAKAN MONTE CARLO EGSnrc

ABSTRAK

Kajian ini berjaya memodel dan mengesahkan pemecut linear Varian Clinac iX untuk tenaga elektron 9 MeV dan 12 MeV menggunakan rangka kerja simulasi Monte Carlo EGSnrc, khususnya modul BEAMnrc dan DOSXYZnrc. Kepala LINAC dibina semula dengan tepat menggunakan sembilan modul komponen (CM) yang mewakili struktur penting seperti kolimator primer, kerajang penyebar, dan aplikator, dengan sifat bahan ditentukan melalui fail 700icru.pegsdat bagi memastikan pemodelan interaksi zarah yang tepat. Fail ruang fasa yang dijana pada jarak sumber-ke-permukaan (SSD) 100 cm digunakan untuk mensimulasikan agihan dos dalam fantom air bervoksel yang menyerupai tetapan klinikal. Data eksperimen dikumpulkan menggunakan kebuk ion selari-rata Markus mengikut protokol IAEA TRS-398, dan digunakan untuk mengesahkan PDD dan profil yang dijana melalui simulasi Monte Carlo. Hasil simulasi menunjukkan kesesuaian yang tinggi dengan nilai ukuran sebenar, dengan perbezaan peratusan bagi parameter R_{100}, R_{90}, R_{50} dan Rp berada dalam had klinikal yang boleh diterima. Nilai kerataan dan simetri juga sepadan dengan pengukuran eksperimen, kecuali sedikit perbezaan pada tenaga 12 MeV yang mungkin disebabkan oleh ketidaktepatan dalam pemodelan geometri. Selain itu, perbandingan dengan anggaran julat elektron berdasarkan kaedah peraturan am turut mengesahkan ketepatan simulasi. Secara keseluruhan, kajian ini menunjukkan bahawa EGSnrc, apabila digabungkan dengan data input yang tepat dan pemodelan geometri yang

terperinci, mampu menghasilkan ramalan dos yang sangat tepat dan sesuai digunakan dalam perancangan rawatan klinikal, jaminan kualiti, dan penanda aras dalam terapi sinaran elektron.

VERIFICATION OF THE RULE OF THUMB TO DETERMINE ELECTRON RANGE PARAMETER USING EGSnrc MONTE CARLO

ABSTRACT

This study successfully models and validates the Varian Clinac iX linear accelerator for 9 MeV and 12 MeV electron beams using the EGSnrc Monte Carlo simulation framework, specifically BEAMnrc and DOSXYZnrc. The LINAC head was accurately reconstructed using nine component modules (CMs), representing key structures such as the primary collimator, scattering foils, and applicator, with material properties defined through the 700icru.pegsdat file for precise particle interaction modelling. A phase space file generated at 100 cm SSD was used to simulate dose distribution in a voxelised water phantom that replicates clinical setups. Experimental data, collected with a Markus plane-parallel ionisation chamber following IAEA TRS-398 protocol, served to validate the MC-generated PDD and beam profiles. The simulation showed strong agreement with measured values, with percentage differences for R_{100}, R_{90}, R_{50}, and Rp within clinically acceptable limits. Beam flatness and symmetry also aligned closely with measurements, aside from slight discrepancies at 12 MeV due to potential geometric modelling issues. Additionally, comparison with rule-of-thumb estimates for electron range parameters confirmed the accuracy of the simulation. Overall, the study demonstrates that EGSnrc, when combined with precise input data and geometric modelling, can produce high-fidelity dose predictions suitable for clinical treatment planning, quality assurance, and benchmarking in electron beam therapy.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Radiotherapy is a medical treatment that uses high-energy radiation to destroy or damage cancer cells. Two common types of radiation used in external beam radiotherapy are photon beams and electron beams. Photon beam therapy, typically delivered using X-rays or gamma rays, penetrates deep into the body and is ideal for treating tumours located within internal organs. In contrast, electron beam therapy is more surface-focused, effectively treating cancers on or near the skin. Both methods are non-invasive and play a crucial role in modern cancer management.

Electron beam therapy remains a vital modality in contemporary radiotherapy, particularly effective for treating superficial tumours due to its limited tissue penetration. Unlike photon beams that travel deeper, electron beams deposit most of their energy at a defined depth known as the depth of maximum dose (D_{max}) and then rapidly diminish in intensity beyond that point. This sharp dose fall-off protects deeper healthy tissues, making electrons ideal for targeting lesions near the skin surface, such as non-melanoma skin cancers, without unnecessary exposure to underlying structures (Valve et al., 2023).

The "rule of thumb" in electron beam therapy provides simplified estimations for various depth-dose parameters, including R50, R90, Rp, and R100, which describe the depth at which specific percentages of the maximum dose are delivered. R50 is the depth at which the dose falls to 50% of the maximum, and is often used to define beam quality and for specifying electron energy. R90 and R100 refer to the depths where the dose reaches

90% and 100% of the maximum dose, respectively, with R90 commonly used in treatment planning to define the therapeutic range. Rp (practical range) represents the depth at which the dose essentially drops to zero.

Additionally, advanced methods like Monte Carlo simulations are used for highly precise treatment planning, modelling complex interactions between the electron beam and tissue to predict the exact dose distribution and electron range (Apaza Veliz et al., 2020). These methods are particularly valuable for optimising treatment plans and ensuring precise delivery of radiation to tumours while minimising collateral damage to surrounding healthy tissues.

Electron Gamma Shower (EGSnrc) is a Monte Carlo (MC) code system designed to simulate the transport of electrons and photons through matter. One of its components, BEAMnrc, is an MC code system specifically designed to simulate the behaviour of radiation beams produced by medical linear accelerators. BEAMnrc generates phase-space files that describe the particles' energy, position, and direction, which can then be used for further simulations. Another component, DOSXYZnrc, uses these phase-space files to calculate dose distributions in phantom geometries. It calculates the energy deposited in each voxel of the phantom, providing detailed dose information essential for treatment planning and optimisation (Grudzinski et al., 2023)

1.2 Problem Statement

The rule of thumb gives a quick estimation in the electron range. There are a few ways to calculate the rule of thumb, for example, for 9MeV:

Table 1.1 Different Methods in Estimating the Rule of Thumb Parameters.

Method	Rule of thumb parameters			
	R100	R90	R50	Rp
In mm (Mott and West, 2021)	9 x 2= 18	9 x 3= 27	9 x 4= 36	9 x 5= 45
In cm (Chang et al., 2021)	9/ 4= 2.3	9/ 3.2= 2.8	9/ 2.3= 3.9	9/ 2= 4.5
% difference	4.14	7.56	14.04	0.00

These varying approaches can lead to significant discrepancies in calculated electron ranges, especially in heterogeneous tissues or complex clinical scenarios. Such inconsistencies can result in underdosing the tumour or overdosing healthy tissue, which compromises treatment accuracy and patient safety (Paschal et al., 2022). For this reason, while useful for quick estimations, the rule of thumb should be supplemented with more precise methods like Monte Carlo simulations for treatment planning.

The inefficiency of detectors in accurately measuring electron range arises primarily from their limitations in spatial resolution, energy dependence, and perturbation of the electron field. Common detectors, such as ionisation chambers, may not provide sufficient resolution to precisely capture steep dose gradients near the end of the electron range, particularly around Rp (practical range) and R90. Additionally, the physical size of some detectors can cause volume averaging effects, leading to an underestimation of the true dose at specific depths.

1.3 General Objective

To validate the rule of thumb in determining the electron range parameter using EGSnrc Monte Carlo.

1.4 Specific Objective

1. To model the treatment head of Varian LINAC for electron beam based on the technical data and information provided by the manufacturer.

2. To validate the LINAC model using IC water phantom dose measurement at energies 9 and 12 MeV using DOSXYZnrc.

3. To compare the rule of thumb formulas of R90, R80, R50, and Rp with the MC calculated value.

CHAPTER 2

LITERATURE REVIEW

In electron beam dosimetry, simple empirical rules of thumb provide clinicians with efficient tools to estimate key range parameters, namely R100, R90, R50 and practical range (Rp) based on the beam's nominal energy E(MeV). These rules are intended as quick clinical approximations and not substitutes for measured data, which remain essential for precise treatment planning and QA (Apaza Veliz et al., 2020).

2.1 The Rule of Thumb

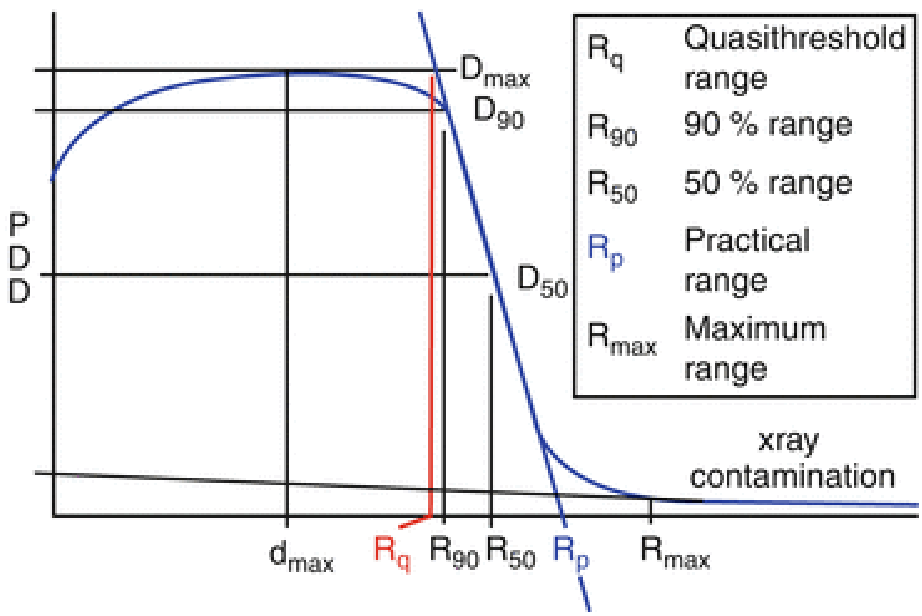

Figure 2.1 Electron range metrics. R90 and R50 are defined by the depth of the 90% and 50 % isodose lines. A straight line is drawn between R90 and R50 and used to calculate extrapolation values. Extrapolating back to 100% gives the Rq, while extrapolating forward to 0 % gives the Rp. Rmax is the maximum range of electrons, after which the dose is entirely due to Bremsstrahlung x-rays *('Dosimetry of Electron Beams | Radiology Key', 2016)*.

Although rules of thumb, such as estimating practical range Rp≈E/2 (cm) or 90% depth dose R90≈E/3.2, offer a convenient and rapid means of estimating electron beam ranges, their reliability is limited in several important clinical scenarios. While convenient, these rules of thumb oversimplify electron transport and omit crucial dependencies, leading to potentially significant errors. These equations assume large, homogeneous fields in water phantoms. However, for small fields or narrow cutouts, lateral charged-particle equilibrium breaks down, and source occlusion alters beam profiles. Quantitative studies have shown that output factors and depth parameters can deviate by more than ±1 mm or several per cent compared to broad-field estimations, particularly with field sizes <2–3 cm (Parveen et al., 2022).

Choosing the appropriate electron beam energy is essential in radiotherapy to ensure that the dose is deposited precisely at the target depth while sparing healthy tissue. MC benchmark studies (Zhang et al., 2020), have shown that even a small mismatch in nominal energy (e.g., ±0.2 MeV) can affect depth-dose accuracy. For example, variations of up to 1.8% in dose distribution were reported for 7 MeV beams, while others observed no significant impact when energy variations were confined within a tighter 0.2 MeV window.

For small field dosimetry, MC calculated dose distributions deviated significantly from measurements when the beam energy was misestimated, particularly in high-gradient regions like the penumbra and umbra. Their results showed up to 40% discrepancies in lateral dose profiles for 20 MeV electrons and over 50% variance in output factors for small fields at 6 MeV (Ali et al., 2022). These variations impact key range metrics such as Dmax, R50, and R90, which define where the dose falls off to therapeutic levels. Inaccurate energy selection can lead to underdosage of the tumour or excess dose beyond the intended depth, compromising both effectiveness and safety.

2.2 Ionisation Chamber, IC

2.2.1 IC Used in Electron Measurement

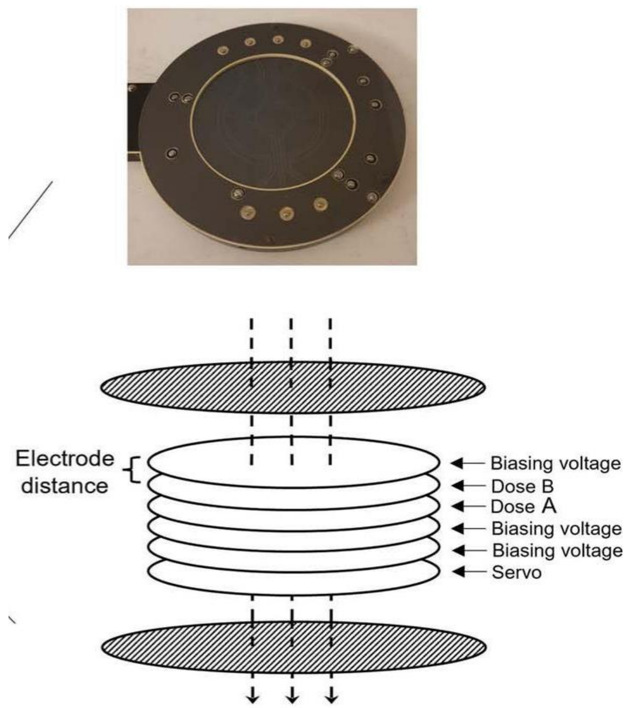

Figure 2.2 Reconfiguring a Plane-Parallel Transmission Ionisation Chamber.

Cylindrical ionisation chambers commonly used in photon dosimetry are inadequate for precise electron beam depth-range measurements, especially in low-to-medium-energy regimes (< 10 MeV). The effective point of measurement (EPOM) for cylindrical chambers is displaced upstream (usually ~0.5 × the cavity radius), and this shift is both energy- and geometry-dependent for electron beams. For instance, many studies found that using the standard EPOM shift leads to systematic errors in percentage depth-dose curves, misplacing critical parameters like R50 and Dmax by up to a few millimetres (Anusionwu et al., 2020). The dose gradient in electron beams means cylindrical chambers suffer from volume-averaging errors: the curved geometry cannot resolve steep depth-dose changes accurately, leading to under- or over-estimation of range endpoints like R90 and R80 (Anusionwu et al., 2020).

2.2.2 Recommend Protocols for Electron Dosimetry

Both the AAPM TG-51 and IAEA TRS-398 protocols recommend plane-parallel chambers as the standard for electron dosimetry, especially for energies below 10 MeV. Cylindrical chambers are only conditionally accepted for higher-energy electrons (>10 MeV) and only when corrections are accurately applied, which introduces further uncertainty (Yulinar et al., 2023) Plane-parallel ionisation chambers are superior for electron beam dosimetry because they offer higher spatial accuracy, less perturbation, and better alignment with protocol recommendations.

Plane-parallel ionisation chambers such as Markus, Roos, and Advanced Markus models have long been the standard for electron beam dosimetry due to their design, which allows for accurate dose measurements at shallow depths. However, despite their widespread use, recent studies from 2020 to 2025 have identified several limitations that affect their accuracy in determining electron beam range parameters such as R90 , R50, Dmax , and practical range (Rp) (Baghani et al., 2022).

2.2.3 Limitation of Plane-parallel IC for Electron Dosimetry

One of the critical limitations lies in the energy-dependent effective point of measurement (EPOM). Yasui et al. (2023) showed that the EPOM of plane-parallel chambers is not fixed but varies with the energy of the electron beam. Their study found that the EPOM shifts deeper into the chamber cavity as energy increases, leading to discrepancies in the measurement of depth-dose parameters unless corrections are applied. For instance, variations of up to 0.4 mm were observed between 6 MeV and 22 MeV when comparing Markus chamber data to reference values obtained using a microDiamond detector, which has a more stable and defined measurement point (Yasui et al., 2023).

In addition, chamber-specific behaviour also contributes to measurement variability. An article evaluated multiple plane-parallel chambers (Markus, Roos, Advanced Markus) in a plastic phantom and reported significant variations in scaling factors used for correcting measured data. These differences, exceeding 4% in some cases, complicate inter-chamber comparisons and introduce uncertainties in the determination of Rp and R50 . Such variability highlights the necessity for individual chamber calibration and correction when used in clinical dosimetry (Baghani et al., 2024).

Furthermore, perturbation effects caused by the chamber walls and the air cavity inside the detector can introduce dose inaccuracies, particularly at shallow depths or near Rp. Monte Carlo simulations have demonstrated that these perturbations can cause measurement deviations of up to 1–2% in low-energy beams (Ghasemi et al., 2021). The physical design of the chamber, such as wall thickness and collector material, contributes to these effects and limits their reliability, especially beyond the depth of maximum dose.

The dependence on field size also restricts the use of plane-parallel chambers in modern treatment setups. A study in 2022 found that larger chambers produced lower percentage depth dose (PDD) readings in small electron fields (>12 MeV) due to reduced lateral electron equilibrium. This discrepancy could shift measured range parameters like R90 or R50 outward by several millimetres, reducing the accuracy of range estimation in clinical scenarios involving small cutouts or complex beam geometries (Russo et al., 2022).

Another significant limitation has emerged with the advent of ultra-high dose rate (UHDR) electron therapy, or FLASH. Standard plane-parallel chambers, which were not designed to handle high instantaneous dose rates, experience significant charge collection issues under FLASH conditions. Ito et al. (2023) found that even optimised chamber designs with ultra-thin electrode spacing (e.g., 0.25 mm) suffer from recombination and space-charge effects, distorting the measured dose and compromising accuracy in range determination. These challenges necessitate either redesigning the chamber for UHDR compatibility or shifting to alternative detectors that can maintain precision at high dose-per-pulse rates.

2.3 Monte Carlo Simulation

MC simulations have become an indispensable tool in radiation therapy, particularly for determining the electron range and optimising dose distributions. These simulations provide high accuracy in modelling the transport of electrons and photons through matter, allowing for precise calculations of dose distributions in complex geometries. This capability is crucial for treatments involving electron beams, where accurate knowledge of the electron range is essential to ensure effective tumour control while minimising damage to surrounding healthy tissues (Franciosini et al., 2023).

One of the primary applications of MC simulations in electron therapy is the calculation of depth-dose distributions. Studies have demonstrated that MC simulations can accurately predict the depth of maximum dose (Dmax), practical range (Rp), and other key parameters such as R50 and R90, which are critical for treatment planning. For instance, a Monte Carlo simulation framework was developed for electron beam dose calculations using Varian phase space files for TrueBeam Linacs. Their results showed excellent agreement between MC simulations and measured data, with differences within 2% or 1 mm for per cent depth dose and orthogonal profiles at various depths, including R100, R50, and Rp. This level of accuracy underscores the reliability of MC simulations in determining electron range and dose distributions (Saidi et al., 2021).

2.3.1 EGSnrc Monte Carlo Simulation

The EGSnrc MC simulation system is a widely used and validated toolkit for modelling electron and photon transport in various media. It operates across energy ranges from 1 keV to 10 GeV and has found extensive applications in medical physics, particularly in radiation therapy, quality assurance (QA), and dosimetry. EGSnrc builds upon the legacy of the EGS4 system, introducing more accurate transport algorithms, improved geometry handling, and variance-reduction techniques to improve simulation efficiency and accuracy(Czarnecki et al., 2023).

In addition to computational advancements, the integration of MC simulations with commercial treatment planning systems has further streamlined their application in clinical practice. For instance, the RayStation treatment planning system incorporates an MC dose calculation algorithm for electron treatment planning that uses the VMC++ Monte Carlo code for in-patient energy transport and scoring. A study evaluated the accuracy of RayStation's electron MC algorithm and found that it provided improved dose calculation accuracy compared to traditional pencil beam algorithms, particularly in complex geometries involving air cavities and bones. This integration allows clinicians to leverage the precision of MC simulations within their existing treatment planning workflows(Wendykier et al., 2023).

2.3.2 BEAMnrc/ EGSnrc

One of the most common clinical uses of EGSnrc is in linear accelerator (LINAC) modelling**.** BEAMnrc and DOSXYZnrc modules to simulate an Elekta Versa HD treatment head, incorporating a detailed linac geometry and using bremsstrahlung splitting to reduce statistical uncertainty. The dose distributions from the simulation closely matched those from the Monaco treatment planning system (TPS), validating EGSnrc as a robust independent dose verification tool in radiotherapy QA (Paschal et al., 2022b).

BEAMnrc is an advanced component of the EGSnrc Monte Carlo toolkit that enables detailed simulation of radiation transport through complex accelerator structures. It models individual LINAC head components such as target, flattening filter, jaws, and multi-leaf collimators by using modular component modules and advanced variance-reduction techniques (e.g., bremsstrahlung splitting, Russian roulette) to optimise computational efficiency and accuracy. The output from BEAMnrc is typically exported as a phase-space file (Sachse and du Plessis, 2019).

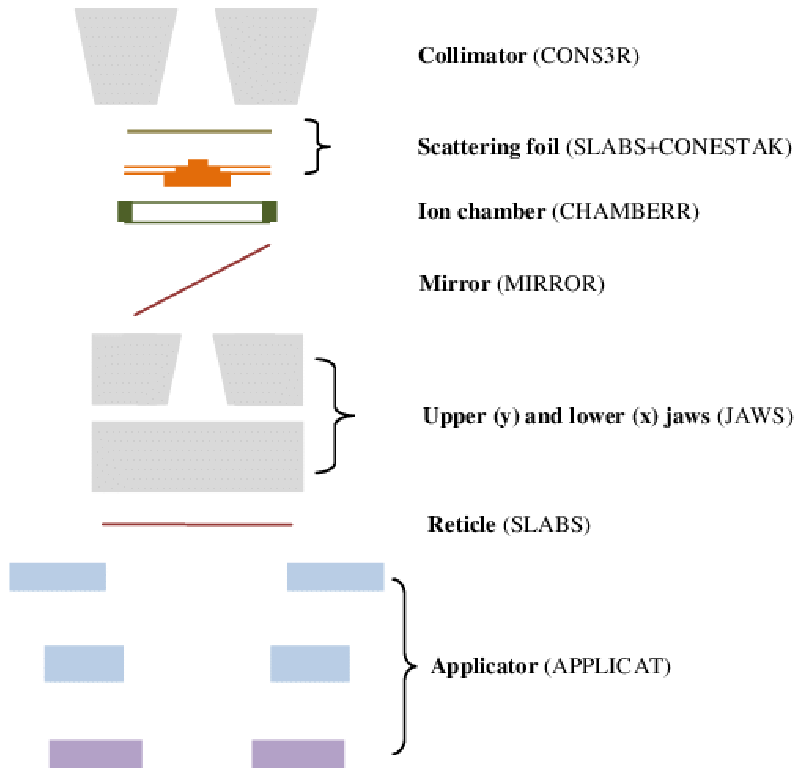

Figure 2.3: Schematic diagram of the Varian 21iX linear accelerator head model, showing components in BEAMnrc for the megavoltage electron beam simulation (Gorjiara et al., 2011).

2.3.3 DOSXYZnrc/ EGSnrc

These phase-space files serve as input for DOSXYZnrc, which scores energy deposition within voxelised geometries such as water phantoms or patient CT datasets to calculate 3D dose distributions with voxel-level resolution. Recent medical physics applications report voxel statistical uncertainties below 0.3–1%, even in complex QA and patient-specific simulations. Together, BEAMnrc and DOSXYZnrc form a powerful, validated workflow for modelling beam characteristics and performing high-fidelity 3D dosimetry in research and clinical quality assurance (Parveen et al., 2022).

2.4 Summary

Despite the advantages, challenges remain in the widespread adoption of MC simulations for determining electron range. These include the need for extensive validation against experimental measurements, particularly in heterogeneous media, and the requirement for specialised knowledge and training to interpret MC simulation results accurately (Iliaskou et al., 2024). In conclusion, MC simulations have proven to be a powerful tool in determining electron range and optimising dose distributions in radiation therapy. Advancements in computational techniques and integration with commercial treatment planning systems have enhanced their applicability in clinical practice (Iliaskou et al., 2024).

CHAPTER 3

METHODOLOGY

3.1 Materials

3.1.1 LINAC Varian Clinac iX

The Varian Clinac iX linear accelerator (Siemens, USA) employs several key components in its treatment head to facilitate precise electron beam therapy. In electron mode, the primary collimator limits the maximum field size, ensuring that the electron beam is appropriately confined. The scattering foils, typically made of high-Z materials like tungsten, are introduced to broaden the narrow electron pencil beam into a uniform fluence across the treatment field. Following this, the ion chamber monitors the beam's dose rate, integrated dose, and field symmetry, providing essential feedback for accurate dose delivery. The mirror directs the electron beam toward the patient, and the pair of movable jaws further shapes the beam to the desired field size. For the simulated electron treatments, a 15×15 cm^2 applicator is used to define the treatment area, ensuring that the electron beam conforms to the planned target volume. These components work in unison to deliver precise and effective electron beam therapy.

Figure 3.1: Varian Clinac iX LINAC (Siemens, USA) at HPUSM

3.1.2 Advanced Markus plane-parallel Chamber Type 34045

The Advanced Markus plane-parallel Chamber Type 34045 is a vented plane-parallel ionisation chamber designed specifically for high-precision electron dosimetry, particularly in high-energy electron beams. It is the modern successor to the classic Markus chamber and features a sensitive volume of 0.02 cm^3, making it ideal for high spatial resolution measurements near the surface in both solid-state and water phantoms. The chamber includes a thin 0.03 mm polyethylene entrance window and a removable 0.87 mm PMMA protection cap, which together provide a water-equivalent thickness of 1.04 mm. The reference point for measurements is located at the inner surface of the entrance window or 1.3 mm beneath the protection cap. With a nominal response of 0.67 nC/Gy, long-term stability of ≤1% per year, and low polarity effect (<1%) for electrons above 9 MeV, it is highly suited for clinical reference dosimetry following protocols like IAEA TRS-398.

The chamber includes a wide guard ring to minimise perturbation and a vented design for atmospheric pressure equilibrium. It maintains directional response within ±0.1% for tilting up to ±10°, and supports a broad operational range, including electron energies from 2–45 MeV. The IC was calibrated in the secondary standard dosimetry laboratory (SSDL) at the Malaysian Nuclear Agency before being used for dose measurement in HPUSM, Kubang Kerian, Kelantan.

Figure 3.2: Plane-parallel Ionisation Chamber with Model of 34045 Markus®

3.1.3 EGSnrc Monte Carlo Simulation

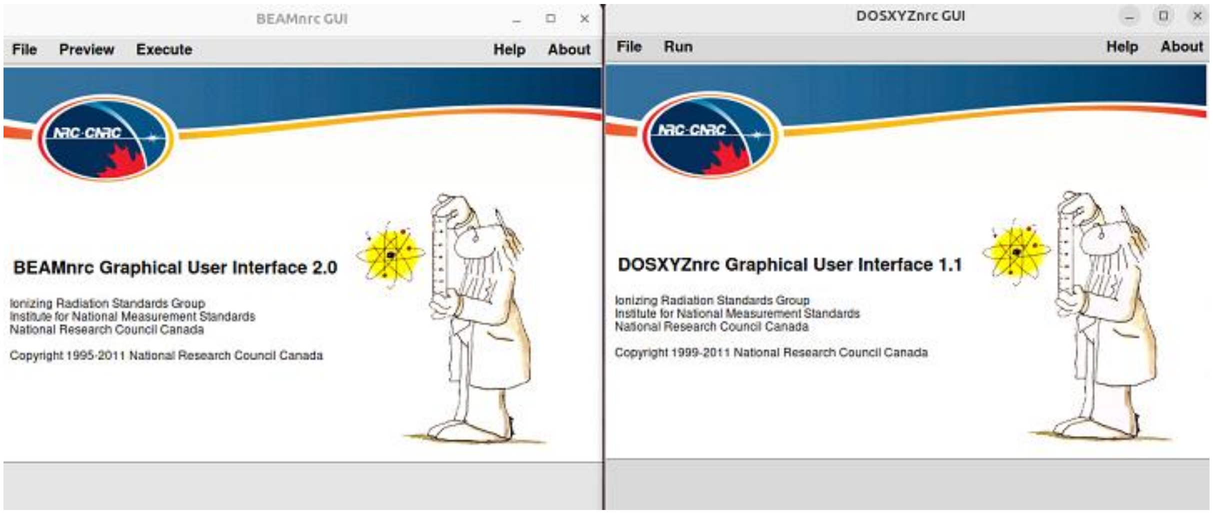

Figure 3.3: EGSnrc user code (a) BEAMnrc GUI 2.0 (b) DOSXYZnrc GUI 2.0

The EGSnrc code system, developed and maintained by the National Research Council of Canada, is a widely utilised Monte Carlo simulation toolkit in medical physics, particularly for radiotherapy applications. It encompasses several user codes, including BEAMnrc and DOSXYZnrc, designed to model a linear accelerator(Fielding, 2023). BEAMnrc simulates the transport of electrons through the linac head, modelling components such as the primary collimator, scattering foil, ion chamber, mirror, jaws, and applicator. This simulation generates phase-space files that serve as input for DOSXYZnrc, which calculates dose distributions in patient-specific phantoms derived from CT imaging. The EGSnrc system employs variance reduction techniques like directional bremsstrahlung splitting to enhance simulation efficiency while maintaining accuracy. These capabilities make EGSnrc a valuable tool for independent dose verification and treatment planning in radiotherapy(Abdoli et al., 2024).

3.2 Method

3.1.1 LINAC Beam Data Measurement

The LINAC beam data measurement was done according to the IAEA TRS-398 protocol. For PDD measurements at 9 and 12 MeV, an applicator with a field size of 15 cm × 15 cm was mounted onto the treatment head of the LINAC using the applicator holder. A water phantom of 40 cm x 40 cm x 40 cm was filled. The source-to-surface distance (SSD) was set to 100 cm using the optical distance indicator (ODI). A plane-parallel ionisation chamber (Markus type) was inserted into the chamber holder and connected to an electrometer located outside the treatment room via a connection cable. The measurement was started at 5 and 7 cm for 9 and 12 MeV, respectively. The PDD were calculated by using the following equation:

$$PDD = \frac{D_d}{D_{max}} \times 100\% \qquad \text{(Eq. 3.1)}$$

Where the D_d is dose at any depth and $D_{max}$is the maximum dose, along the central axis of the irradiated beam.

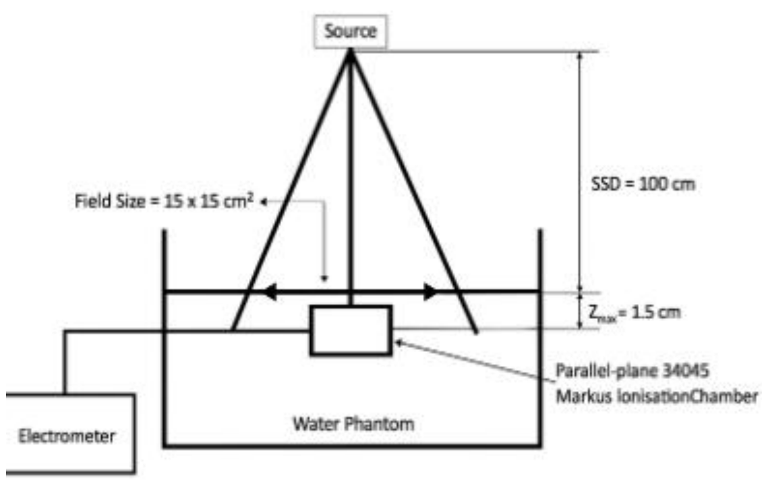

Figure 3.4: Beam data measurement with SSD 100cm with field size 15 cm x 15 cm for 9 and 12 MeV

Meanwhile, for the beam profile measurement, the depth of measurement started at 7 cm and 9.5 cm were done for 9 and 12 MeV, respectively. For the cross-plane profile, the IC moved across the x-axis of the water phantom, while for the in-plane profile, the IC moved across the y-axis of the water phantom (Figure 3.4). The measured data of PD and beam profile were used to validate against the calculated data obtained from the modelled LINAC in EGSnrc.

3.1.2 LINAC Treatment Head Modelling using BEAMnrc/ EGSnrc

In this study, the Varian Clinac iX linear accelerator (LINAC) was modelled using the BEAMnrc/EGSnrc Monte Carlo simulation code. The treatment head configuration was developed based on detailed technical specifications and proprietary information supplied by the manufacturer (Varian, USA), under the terms of a non-disclosure agreement (NDA) established prior to the commencement of the study.

A total of 9 CM was used in this study for modelling the Varian Clinac iX LINAC as shown in Table 3.1, and with the region between the CM filled with air.

Table 3.1: BEAMnrc CM in modelling the Varian Clinac iX

LINAC Components	BEAMnrc Component Module, CM
Primary Collimator	CONS3R
Window	SLAB
Scattering Foils	SLAB + CONESTAK
Ion Chamber	CHAMBER
Mirror	MIRROR
Jaws	JAW
Applicator	APPLICAT
Exit Air	SLAB

In this study, various EGSnrc CM were employed to model specific parts of the linear accelerator head with high precision. The CONS3R CM, composed of a stack of three truncated conical regions, was used to represent the primary collimator. The CHAMBER CM, featuring a symmetric cylindrical planar geometry with an embedded parallel-plate ionisation chamber, was utilised to model the ion IC. The CONESTAK CM, capable of simulating stacked conical or cylindrical geometries, was applied to model the scattering foil. The SLABS CM, defined by a square or rectangular boundary containing multiple material layers of arbitrary composition and thickness, was used to model the window, the primary layer of the scattering foil, and the exit air region. The MIRROR CM, which allows for the definition of an arbitrary number of layers at any angle relative to the z-axis, was implemented to model the LINAC mirror. Additionally, the JAW CM was used to represent the movable collimator jaws responsible for shaping the radiation field.

Finally, the APPLICAT CM was employed to simulate the electron applicator, which directs and shapes the electron beam before it reaches the patient.

Figure 3.5 presents the schematic diagram of the modelled Varian Clinac iX LINAC. The mass density, atomic number, and electron density of all materials used in the LINAC modelling were sourced from the 700icru.pegsdat file, which was duplicated and renamed as 700icru_varianIffah(1).pegsdat within the EGS_GUI interface. Additional custom materials were then defined and incorporated for use in the BEAMnrc simulation of the LINAC. A field size of 15 cm × 15 cm was applied during both simulation and measurement processes.

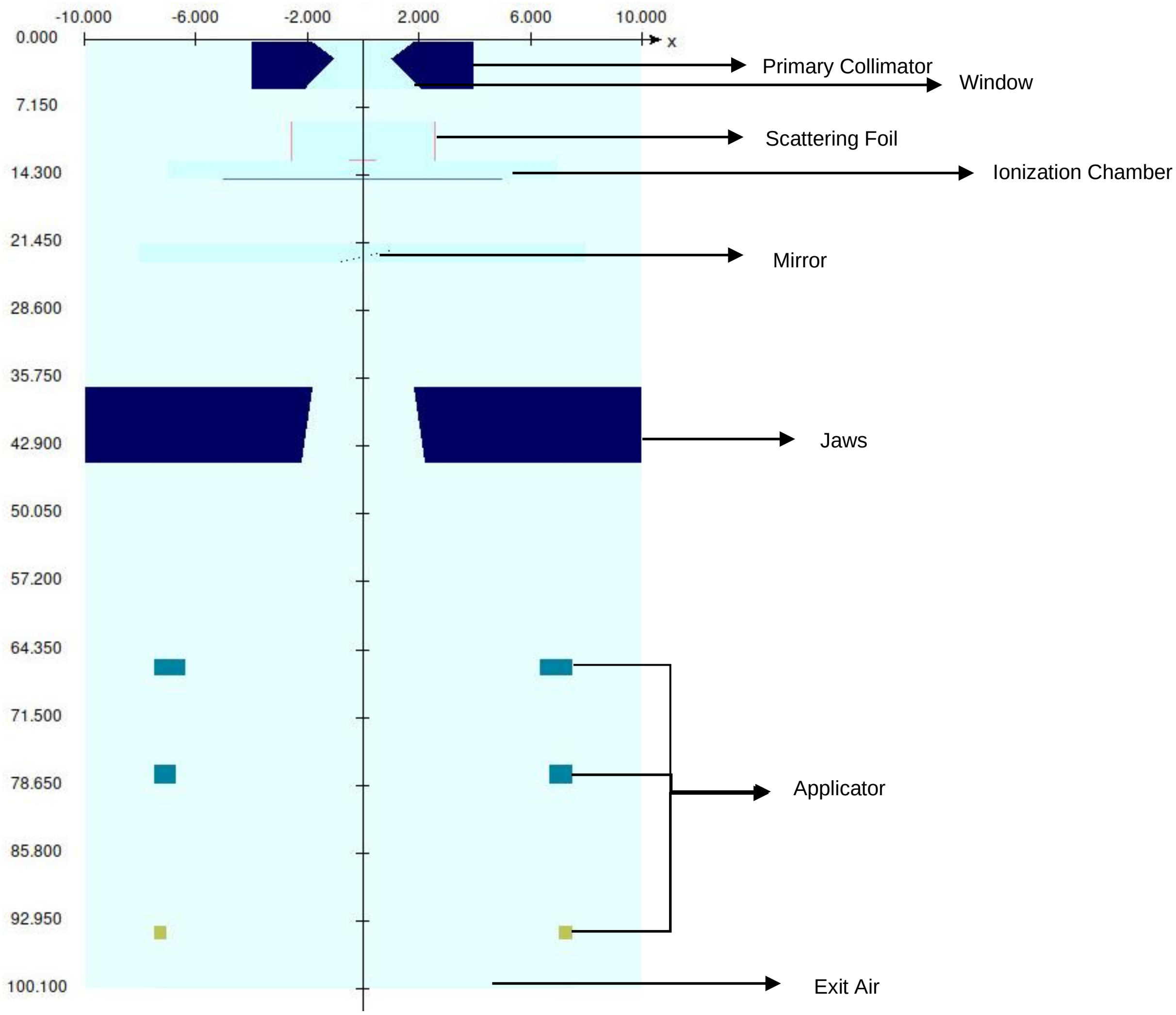

Figure 3.5: Modelled LINAC in BEAMnrc/EGSnrc

3.1.3 BEAMnrc/ EGSnrc Parameters

Several key parameters were defined in BEAMnrc/EGSnrc before initiating the simulation process. Table 3.2 summarises the simulation parameters applied during the execution of the modelled LINAC in the BEAMnrc/EGSnrc.

Table 3.1: Parameters used in BEAMnrc/ EGSnrc

Parameters	Value
Particle histories	1×10^9
Score last Z option	X-Y-Z of last interaction
Incident electron beam	ISOURC 19- alliptical beam source with Gaussian distribution in X and Y directions, with parallel or with radial divergence
Global electron cut-off energy (ECUT)	0.7 MeV
Global photon cut-off energy (PCUT)	0.01 MeV
Electron-step algorithm	PRESTA-II

The phase spaces file was positioned at 100 cm from the source to equal with the LINAC beam data measurement setup for IC measurement. The incident electron kinetic energy of 9 and 12 MeV was used in this simulation. The information about the particle histories, including the particle's position, direction and energy, was kept in the phase space file after the simulation process in BEAMnrc/EGSnrc was completed.

3.1.4 Dose calculation in DOSXYZnrc/ EGSnrc

The phase space file generated from the BEAMnrc/EGSnrc simulation, as described (Section 3.2.3), was utilised as input for calculating the dose distribution within a three-dimensional voxelised water phantom using DOSXYZnrc/EGSnrc. The phantom dimensions were 40 cm × 40 cm × 40 cm, with individual voxel sizes of 0.4 cm × 0.4 cm × 0.1 cm and a uniform density of 1 g/cm³. The H2O700ICRU material definition from the