DOSIMETRIC VERIFICATION OF MONACO TREATMENT PLANNING SYSTEM (TPS) IN HETEROGENEOUS MEDIUM FOR 6 MV LINAC

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UNIVERSITI SAINS MALAYSIA

2024

DOSIMETRIC VERIFICATION OF MONACO TREATMENT PLANNING SYSTEM (TPS) IN HETEROGENEOUS MEDIUM FOR 6 MV LINAC

by

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Dissertation submitted in partial fulfilment

of the requirements for the degree of

Bachelor of Health Science (Honours) (Medical Radiation)

July 2024

ACKNOWLEDGEMENT

All praises and thanks to Allah for His blessings and mercy in granting me the strength and perseverance to successfully complete this dissertation project. Without His grace and guidance, this achievement would not have been possible.

I would like to extend my deepest gratitude to my supervisor, Dr. Jayapramila A/P Jayamani, whose constant support, supervision, and invaluable insights were instrumental throughout this journey. Her dedication to guiding me through the complexities of this research was remarkable. Her constructive comments and extensive knowledge greatly contributed to the successful attainment of the objectives of this study. I was profoundly grateful for her patience and unwavering commitment, which inspired and motivated me to strive for excellence.

Special appreciation was also extended to my co-supervisor, Mr. Reduan bin Abdullah, for his supportive comments and assistance regarding the methodological aspects of this research. His expertise and guidance were crucial in refining the methods employed in this study. I deeply appreciated his willingness to provide support and his constructive feedback, which significantly enhanced the quality of this work.

CERTIFICATE

This is to certify that the dissertation entitled "DOSIMETRIC VERIFICATION OF MONACO TREATMENT PLANNING SYSTEM (TPS) IN HETEROGENEOUS MEDIUM FOR 6 MV LINAC" is the bona fide record of research work done by Ms "ADRIANA BATRISYIA BINTI NOOR MOHD AZLAN" during the period from August 2023 to July 2024 under my supervision. I have read this dissertation and that 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 Health Science (Honours) Medical Radiation Programme.

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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. This work is a culmination of my individual efforts, alongside the guidance and support received from my advisors and collaborators, whose contributions are clearly acknowledged throughout this document. I affirm that this dissertation has not been previously or concurrently submitted, either in part or as a whole, for any other degrees or qualifications at Universiti Sains Malaysia or any other institutions of higher learning. Furthermore, I hereby grant Universiti Sains Malaysia the perpetual, non-exclusive right to utilize this dissertation for purposes including, but not limited to, teaching, research, and promotional activities. This permission encompasses the reproduction and distribution of the dissertation in any medium, as well as the adaptation, translation, and public display of the work. I acknowledge the university's role in supporting my research and am pleased to contribute to the academic and scholarly resources available at Universiti Sains Malaysia. By making this declaration, I reaffirm my commitment to academic integrity and the pursuit of knowledge, ensuring that all ethical guidelines and institutional requirements have been rigorously followed in the preparation and submission of this dissertation.

……

Adriana Batrisyia Binti Noor Mohd Azlan

Date: 31st July 2024

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LIST OF SYMBOLS

Z	Atomic number
R	Average reading of all TLD
°	Degree
Δd^2	Distance-to-agreement
D	Dose
ΔD^2	Dose difference
D_2	Dose received by 2% of volume
D_{50}	Dose received by 50% of volume
D_{98}	Dose received by 98% of volume
I	Exposed film
γ	Gamma
CF_i	Individual calibration factor
<	Less than
D_{max}	Maximum dose received by volume
D_{mean}	Mean dose received by volume
μm	Micrometer
D_{min}	Minimum dose received by volume
>	More than
%	Percentage
±	Plus, or minus
Ri	Reading of each individual TLD
Si	Sensitivity correction factor
I_o	Unexposed film
$V_{95\%}$	Volume covered by at least 95% of prescribed dose

LIST OF ABBREVIATIONS

3DCRT	Three-Dimensional Conformal Radiation Therapy
AAA	Anisotropic Analytical Algorithm
AAPM	American Association of Physicists in Medicine
CBCT	Cone Beam Computed Tomography
CCC	Collapsed Cone Convolution
CI	Conformity Index
CT	Computed Tomography
DD	Dose Difference
DICOM	Digital Imaging and Communications in Medicine
DIMRT	Dynamic Imagery Guided Modulated Radiation Therapy
DOSM	Department Of Statistics Malaysia
DTA	Distance To Agreement
DVH	Dose Volume Histogram
DVO	Dose Volume Optimizer
EBRT	External Beam Radiation Treatment
EBT3	Extended Beam Therapy 3
EPID	Electronic Portal Imaging Device and
FOV	Field of View
HI	Homogeneity Index
HUSM	Hospital Universiti Sains Malaysia
ICRU	International Commission on Radiation Units and Measurements
IMRT	Intensity-Modulated Radiation Therapy
IRT	Internal Radiation Therapy
JEPeM	Jawatankuasa Etika Penyelidikan Manusia
LINAC	Linear Accelerator
MABS	Multi-Atlas-Based Segmentation
MC	Monte Carlo
MLC	Multi Leaf Collimator
MOSFETS	Metal-Oxide-Semiconductor Field-Effect Transistors
MRI	Magnetic Resonance Imaging
NPC	Nasopharyngeal cancer

NTCP	Normal Tissue Complication Probability
OAR	Organs At Risk
OD	Optical Density
PB	Pencil Beam
PSQA	Patient-Specific Quality Assurance
PTV	Planning Target Volume
QA	Quality Assurance
QUANTEC	Quantitative Analysis of Normal Tissue Effects in The Clinic
ROI	Region Of Interest
RTOG	Radiation Therapy Oncology Group
SPSS	Statistical Package for The Social Sciences
SSD	Source-to-Surface Distance
SSIMRT	Segmental Simultaneous Integrated Modulated Radiation Therapy
TCP	Tumour Control Probability
TLD	Thermoluminescence Dosimeter
TPS	Treatment Planning System
TRS	Technical Report Series
USM	Universiti Sains Malaysia
VMAT	Volumetric-Modulated Arc Therapy
VMC++	Voxelized Monte Carlo++
WBRT	Whole Brain Radiotherapy
WHO	World Health Organization
XVMC	X-Ray Voxelized Monte Carlo

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PENGESAHAN DOSIMETRI SISTEM PERANCANGAN RAWATAN MONACO (TPS) DALAM MEDIUM HETEROGEN UNTUK 6 MV LINAC

ABSTRAK

Sistem perancangan rawatan (TPS) Monaco, yang menggunakan algoritma pengiraan dos Monte Carlo (MC) menawarkan ketepatan tinggi dalam perancangan radioterapi. Pengiraan dos yang tepat dalam tisu heterogen memerlukan proseskomisioning dan pengesahan yang komprehensif kerana boleh memberi kesan mendalam kepada hasil pesakitKajian ini menilai ketepatan pengiraan dos Monaco TPS menggunakan bahagian kepala phantom Rando, meter dos termopendarcahaya (TLD-100), filem Gafchromic EBT3, dan data pesakit klinikal melalui jaminan kualiti khas pesakit (PSQA). **Kaedah:** Pengesahan dosimetri Monaco TPS dijalankan pada phantom kepala dan leher Rando untuk perancangan radioterapi konformal 3D (3DCRT) untuk radioterapi otak seluruh (WBRT) dan perancangan volumetric modulated arc therapy (VMAT) untuk meningioma dalam persekitaran heterogen, menggunakan 12 TLD-100 dan filem Gafchromic EBT3. Selain itu, enam pelan pesakit dari Eclipse TPS telah direplikasi pada Monaco TPS, dan PSQA dilaksanakan menggunakan kriteria gamma dengan perbezaan dos 3% (DD) dan jarak-ke-perjanjian 3 mm (DTA). **Keputusan :** Monaco TPS menunjukkan perbezaan peratusan yang konsisten dalam lingkungan ±10% (antara 1.8% hingga 9.1%) antara dos yang dikira TPS dan dos yang diukur oleh TLD untuk 3DCRT, tanpa perbezaan yang signifikan ($p>0.05$). Dosimetri filem Gafchromic EBT3 sangat bersetuju dengan taburan dos TPS, mencapai kadar lulus gamma 97.3%. Walau bagaimanapun, perancangan VMAT menunjukkan perbezaan yang signifikan (antara 3.06% hingga 67.88%) antara dos yang dikira dan dos yang diukur, dengan perbezaan signifikan ($p < 0.01$) dan kadar lulus gamma 52.5% untuk dosimetri filem. PSQA untuk enam pelan pesakit menunjukkan kadar lulus gamma yang tinggi (97.5%

hingga 100%) dan perbezaan dos mutlak antara 0.29% hingga 3.48%. **Kesimpulan :** Monaco TPS adalah boleh dipercayai dan berjaya dikomision dengan tepat untuk perancangan 3DCRT tetapi menunjukkan perbezaan yang signifikan dalam perancangan VMAT. Usaha masa depan harus fokus pada peningkatan kaedah pengesahan, menangani cabaran dalam analisis indeks gamma, dan meningkatkan ketepatan pengiraan dos VMAT untuk perancangan rawatan yang konsisten.

DOSIMETRIC VERIFICATION OF MONACO TREATMENT PLANNING SYSTEM (TPS) IN HETEROGENEOUS MEDIUM FOR 6 MV LINAC

ABSTRACT

The Monaco TPS, employing the Monte Carlo dose calculation algorithm, offers high precision in radiotherapy planning. Accurate dose calculation in heterogeneous tissues necessitates comprehensive commissioning and verification due to its impact on patient outcomes. This study evaluates the dose calculation accuracy of Monaco TPS using Rando phantoms, thermoluminescence dosimeters (TLD-100) dosimeters, EBT3 Gafchromic films, and clinical patient data through patient-specific quality assurance (PSQA). **Methods :** Dosimetric verification of Monaco TPS was conducted on a head and neck Rando phantom for 3D conformal radiotherapy (3DCRT) whole brain radiotherapy (WBRT) and volumetric modulated arc therapy (VMAT) meningioma planning in heterogeneous environments, using 12 TLD-100s and EBT3 Gafchromic films. Additionally, six Eclipse TPS patient plans were replicated on Monaco TPS, and PSQA was performed using gamma criteria of 3% dose difference (DD) and 3 mm distance-to-agreement (DTA). **Results :** Monaco TPS demonstrated consistent percentage deviations within ±10% (ranging from 1.8% to 9.1%) between TPS calculated and TLD-measured doses for 3DCRT, with no significant difference ($p > 0.05$). EBT3 Gafchromic film dosimetry showed good agreement with TPS dose distributions, achieving a 97.3% gamma passing rate. However, VMAT planning revealed significant deviations (3.06% to 67.88%) between calculated and measured doses, with a significant difference ($p < 0.01$) and a 52.5% gamma passing rate for film dosimetry. PSQA for six patient plans yielded high gamma passing rates (97.5% to 100%) and absolute dose deviations ranging

from 0.29% to 3.48%. **Conclusion** : Monaco TPS is reliable and accurately commissioned for 3DCRT planning but shows significant deviations in VMAT planning. Future efforts should aim to improve verification methods, address challenges in gamma index analysis, and enhance VMAT dose calculation accuracy for consistent treatment planning.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Cancer comprises various conditions characterized by uncontrolled abnormal cell growth that can arise in any organ or tissue, with these cells proliferating, infiltrating nearby tissues, and potentially metastasizing to distant organs. (WHO, 2019). As per the World Health Organization (WHO), cancer stands as the primary global cause of death, causing over 10 million deaths in 2020, representing one in six fatalities (World, 2022). According to the 2023 report from the Department of Statistics Malaysia (DOSM), cancer ranked as the fourth most common cause of death in Malaysia, rising from 10.5 percent in 2021 to 12.6 percent in 2022 (Nurul Shahamah, 2024).

Radiation therapy, also known as radiotherapy, is a cancer treatment employing high levels of radiation to eliminate cancerous cells and reduce tumour size (National Cancer Institute, 2019). The most prevalent type of radiotherapy treatment delivery is the external beam radiation treatment (EBRT) which uses linear accelerator (LINAC) machine to deliver high-energy beams to the targeted tumour region (Mayoclinic, 2023).

The radiation process encompasses five key stages: initial consultation, simulation, treatment planning, therapy delivery, and post-treatment follow-up. Ensuring precise dose calculation is crucial for the safe and efficient delivery of radiation therapy to patients. The International Commission on Radiation Units and Measurements (ICRU) report 83 advises maintaining a total dose uncertainty tolerance of 5% in patients, with reducing dose calculation uncertainty serving as a means to achieve this target (Snyder *et al.*, 2018). A TPS a computerised tool, plays a crucial role in determining optimal beam

configurations, energies, field sizes, and the radiation fluence pattern during treatment (Oncology Medical Physics, 2019).

Numerous TPS are presently accessible in the market. Monaco is one of the TPS that integrates the Monte Carlo (MC) dose calculation algorithm for precision, along with robust optimization tools. This combination allows for the generation of high-quality radiotherapy treatment plans using both forward and inverse planning techniques (Clements *et al.*, 2018). In forward planning such as three-dimensional conformal radiation therapy (3DCRT), the planner arranges beams within a radiotherapy system to deliver sufficient radiation to the tumour while safeguarding vital organs and minimizing radiation exposure to healthy tissue. In inverse planning, which widely used techniques such as intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT), a radiation oncologist identifies a patient's critical organs and tumour, followed by a planner assigning target doses and importance factors for each. Subsequently, an optimization program is utilized to identify the treatment plan that best aligns with all specified criteria (Wikipedia Contributors, 2024). To guarantee the accuracy and reliability of treatment plans, commissioning is essential, aiming to minimize the risk of errors that could potentially jeopardize patient safety.

Before the clinical use of a TPS, the commissioning process must be conducted. According to Technical Report Series (TRS) 430, the commissioning process involves extensive measurements of dosimetry and non-dosimetry parameters required to validate the TPS (Mahmoudi, Mostafanezhad & Zeinali, 2022). Commissioning also entails entering beam data into a TPS and validating its correctness, developing operating protocols, and training of all concerned with the operation of the accelerator. Beam data such as measurements of percentage depth dose profiles, output factors, transmission

factors such as wedges and other attenuators will be measured using linear accelerator and water phantom. After commissioning, validations of TPS must be conducted according to American Association of Physicists in Medicine (AAPM) Medical Physics Practice Guideline 5.a (Smilowitz *et al.*, 2015).

The accuracy of dose calculation algorithms is critical in producing accurate dose distributions that give the required or intended dose. Concern arises for very heterogeneous tissues, where a very precise modelling of the patient's energy flow is necessary (Oelfke *et al.*, n.d.). Variations in human tissues, such as the lungs, air cavities, bones, soft tissue, and fat, pose challenges to dose calculation algorithms as they can disrupt the equilibrium of charged particles. Such discrepancies can lead to unacceptable differences between computed and delivered dosages, potentially resulting in misleading treatment plans.

The effectiveness of radiation treatment planning depends on various factors, starting with the commissioning and quality management of the TPS. This includes careful consideration of its measured input data and a comprehensive understanding of TPS models and constraints. The process requires stringent quality assurance measures throughout planning and is connected to the deliverability of the plan, which can be assessed and validated (Hansen *et al.*, 2022). Achieving precision in LINAC dose measurement is crucial, and it should be compared to the accurate calculations provided by the TPS (Goodall *et al.*, 2023). The passing rate of treatment planning is often evaluated using gamma analysis, with a widely accepted standard of 3 mm distance to agreement (DTA) /3% dose difference (DD) for a 90% passing rate in clinical settings (Das S *et al.*, 2022).

In this study, a new Monaco TPS was recently installed in radiotherapy department in Hospital Universiti Sains Malaysia (HUSM), hence in this study, dosimetric verification of the Monaco TPS will be verified using both heterogeneous medium and clinical patient data.

1.2 Problem statement

The primary goal of radiotherapy is to give a sterilising dose of radiation to the tumour in order to destroy malignant cells while sparing healthy organs and tissues (Zarepisheh M *et al.*, 2022). According to TRS report 430, a newly installed TPS for clinical purposes should be completely verified and checked all of features of modules, dose calculations and evaluation tools as well (Lam B, 2016).

Errors in commissioning can have a devastating impact on patients. A hospital in Panama accepted beam data of additional block entry into TPS without giving a warning and calculated incorrect treatment delivery, and 28 patients were affected while five people had died as a result of a radiation overdose (IAEA, 2017). Uncertainties in the TPS dosage computation might result from error in the initial measured beam data collection, input of beam information into TPS and beam data utilisation.

Following that, the accuracy of dose calculation algorithms is critical in producing accurate dose distributions that give the required or intended dose. Dose computations in heterogeneous tissues present significant challenges, necessitating precise modelling of the patient's energy flow (Oelfke *et al.*, n.d.). Human anatomical variations, such as lung tissue, bone structures, and soft tissues, can disrupt the equilibrium of charged particles. This disruption causes electronic disequilibrium and reduced dose deposition near heterogeneous regions, affecting dose calculation algorithms. Radiation dosimetry is particularly impacted by these inhomogeneities, which alter the intensity and scattering

characteristics of the photon beam (Mishra *et al.*, 2023). Errors in dose calculations within these areas can lead to disparities between planned and delivered doses, posing risks to treatment efficacy and patient well-being. Hence, it is imperative for TPS to meticulously account for tissue heterogeneity effects to ensure accurate delivery of radiation therapy.

Hence, dosimetry verification of Monaco TPS using heterogeneous Rando phantom and patient data will be performed to validate the accurate installation of Monaco TPS in Hospital Universiti Sains Malaysia (HUSM).

1.3 Objective

1.3.1 General objective

The main objective is to verify the dosimetry of the Monaco TPS in a heterogeneous medium and clinical usage for 6 MV LINAC in Hospital Universiti Sains Malaysia.

1.3.2 Specific objective

i. To plan 3D-CRT and VMAT treatment planning on head and neck region on Rando Phantom.

ii. To evaluate the dosimetric accuracy of the Monaco TPS using TLD-100 and EBT3 Gafchromic film dosimeters on Rando phantom.

iii. To replicate the Eclipse TPS patient treatment plans on the Monaco TPS for the purpose of assessing clinical applicability through PSQA.

1.4 Study hypothesis

1.4.1 Null hypothesis

i. There is no significant difference between calculated and measured dose in Monaco TPS ($p>0.05$).

ii. The gamma passing rate exceed more than 95% for 3%/3mm in PSQA analysis.

1.4.2 Alternative hypothesis

i. There is significant difference between calculated and measured dose in Monaco TPS ($p<0.05$).

ii. The gamma passing rate is less than 95% for 3%/3mm in PSQA analysis.

1.5 Research question

i. How well do the calculated doses in Monaco TPS agree with measurements using various dosimetric verification tools (TLD-100 and EBT3)?

ii. How does the dose calculation accuracy of Monaco TPS in heterogenous medium?

iii. Has Monaco TPS been successfully commissioned for clinical use?

1.6 Significance of study

Validating TPS ensures confidence in plan precision, enhancing patient safety and treatment efficacy by detecting and rectifying planning errors. This process advances radiation oncology by establishing quality assurance standards, confirming that calculated doses align with prescribed ones, and fostering clinical confidence in TPS-generated plans. Dosimetric validation supports quality assurance, regulatory compliance, and confidence among healthcare professionals in radiation therapy techniques, enhancing treatment precision and minimizing the risk of under- or over-dosage. Moreover, it

benefits medical physicists and radiation specialists by improving understanding of TPS algorithms, optimizing treatment effectiveness, and reducing injury to healthy tissues.

Correct TPS commissioning is essential to ensure accurate dose distribution, especially in heterogeneous tissues, improving radiotherapy quality and organ protection. This study serves as valuable recommendations for consistent and dependable TPS implementation, potentially driving further research into novel radiation technology and personalized medicine approaches. In addition, this work has the potential to serve as recommendations for medical physicists throughout the commissioning of TPS, which is a noteworthy accomplishment. It may serve as a helpful reference for experts, ensuring that TPS is implemented consistently and reliably while adhering to the greatest accuracy and safety requirements. The findings may potentially drive more research into novel radiation technology, treatment strategies, or personalised medicine approaches.

CHAPTER 2

LITERATURE REVIEW

2.1 Brain metastasis

The brain, housed within the skull and cushioned by cerebrospinal fluid, is one of the body's most crucial and intricate organs. The brain is divided into three primary sections as illustrated in Figure 2.1, the cerebrum, the cerebellum, which handles coordination and balance, and the brain stem, which manages automatic functions (Physiopedia, 2015).

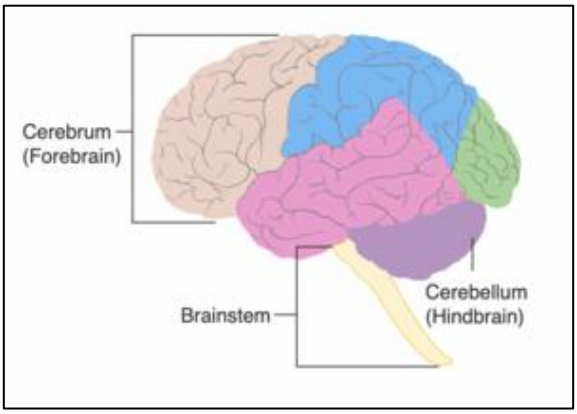

Figure 2.1: Anatomy of cerebrum, brainstem and cerebellum of the brain

A brain tumor, also known as an intracranial tumor, is a mass of abnormal cells inside the skull that multiply uncontrollably, disrupting the normal cellular control mechanisms (LeWine, 2023). These tumors can either be benign, which means they are not cancerous, or malignant, which means they are cancerous. As shown in Figure 2.2, brain tumors can develop from various parts of the brain and its surrounding structures (Warnick, McPherson and Gozal, 2018). They may arise from nerves (neuromas), the brain's outer membrane (meningiomas), or the pituitary gland (such as craniopharyngiomas or pituitary adenomas). Some tumors also originate directly in the brain tissue itself (gliomas). As they grow, these tumors can compress and damage healthy brain tissue, causing a range of symptoms.

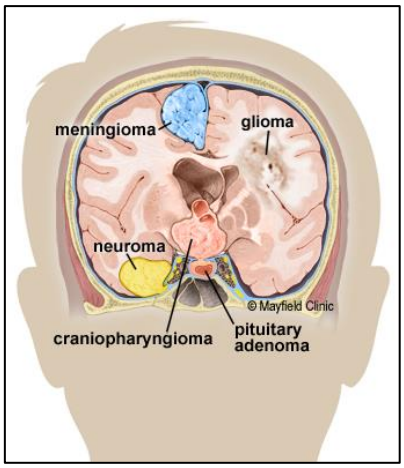

Figure 2.2: Brain tumors development from different parts of the brain and its surrounding structures (Warnick, McPherson and Gozal, 2018).

2.2 Diagnosis and treatment for brain cancer

The approach to treating a brain tumor depends on its size, type, and location, as well as the patient's age and health. Common treatments include surgery, radiation therapy, and chemotherapy, often used in combination, such as surgery followed by radiation therapy. Radiation therapy, which uses high-energy x-rays to kill cancer cells, is typically used when surgery is not possible. It's also used after surgery to deal with any remaining tumor cells or parts that couldn't be removed surgically (Warnick, McPherson and Gozal, 2018).

2.3 Radiotherapy

Radiotherapy is a commonly utilized approach in cancer treatment which uses high-energy radiation to target and destroy cancer cells while attempting to minimize damage to surrounding healthy tissue (National Cancer Institute, 2019). This treatment works by causing small breaks in the DNA within the cells, which disrupts the ability of cancer cells to grow and multiply (American Cancer Society, 2018). The body naturally gets rid of damaged cells when they die. This non-painful cancer treatment effectively shrinks

tumors, removes any remaining cancer cells after surgery (known as adjuvant therapy), and is typically used before other cancer treatments. A specialized team, including radiation oncologists, radiation therapists, medical physicists, and medical dosimetrists, works together to carefully plan and administer the best possible cancer treatment to patients. EBRT and Internal Radiation Therapy (IRT) are the two main types of radiation treatment (Mayo Clinic, 2022). EBRT uses a machine called a linear accelerator, or LINAC, to aim high-energy radiation beams at the tumor. Special computer software called a TPS helps adjust the beam's size and shape for precise targeting of the tumor, while protecting nearby healthy tissue. On the other hand, brachytherapy is a type of internal radiation therapy where radioactive material is placed directly into or near the cancer through permanent or temporary implants.

2.3.1 Radiotherapy workflow

Radiation therapy involves five main steps: initial consultation, simulation, treatment planning, treatment delivery, and post-treatment follow-up (Stony Brook Cancer Organization, 2023). In the consultation phase, a radiation oncologist evaluates the patient's medical history, pathology reports, radiology images, and conducts a physical examination to decide if radiation therapy is appropriate. If approved, the patient proceeds to simulation, where the exact area for treatment is identified using Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) scans, and immobilization devices are set up for precise positioning. Next, the simulation image is used by radiation oncologists, medical physicists, and dosimetrists to develop a detailed treatment plan with TPS, determining the radiation amount and its delivery to minimize impact on healthy tissue. This plan is carried out using a LINAC, which administers high-energy radiation as per the plan's specifications. The frequency and length of sessions vary based on the cancer's type and stage. Lastly, patients undergo post treatment follow-up visits to

monitor their recovery, manage side effects, and evaluate the treatment's success, with ongoing care to address any long-term health effects from the therapy

2.3.2 LINAC principle and component

A LINAC is an advanced machine predominantly used in medical settings to administer external beam radiation therapy for cancer patients. It comprises multiple components that ensure the LINAC functions effectively and safely, delivering accurately controlled radiation doses that specifically target cancer cells while minimizing exposure to healthy surrounding tissues. These components include the accelerating waveguide, bending magnet, circulator, cooling system, electron gun, energy selector, klystron or magnetron, treatment head, and waveguide as illustrated in Figure 2.3 (Oncology Medical Physics, 2019).

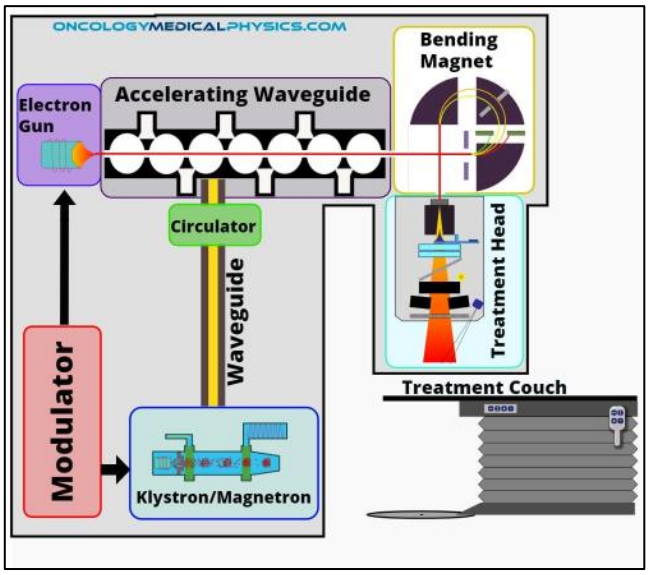

Figure 2.3 : Components in LINAC (Oncology Medical Physics, 2019).

In the treatment head of LINAC as shown in Figure 2.4, an electron gun generates electrons by heating a filament, which then emits electrons. These electrons are initially accelerated by a low electric field and directed through an accelerating waveguide composed of microwave resonance cavities to boost their energy. Microwaves are

generated by a Klystron or Magnetron and conveyed via a waveguide filled with insulating gas to prevent arcing. The beam is shaped and steered using bending magnets and may pass through an energy selector to refine its energy range. The treatment head finalizes beam shaping with targets, scattering foils, and collimators before the beam is used for therapy. Essential components like cooling systems maintain operational stability, and a circulator prevents microwave energy from flowing backward.

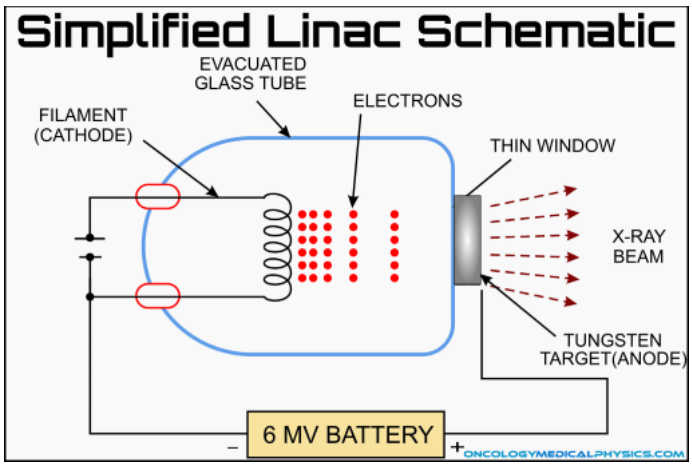

Figure 2.4 : Principle of LINAC treatment head (Oncology Medical Physics, 2019).

2.3.3 Calibration of LINAC

LINAC calibration is a critical component of radiation therapy that involves fine-tuning various settings and parameters of the LINAC to ensure that the delivered radiation doses are both precise and consistent. This process includes confirming the beam energy, shaping the beam accurately, and validating the dose rate. To assess and verify the LINAC's performance, specialized dosimeters and quality assurance tools are utilized (Mercurius Health, 2023).

Before a LINAC can be used clinically, it must undergo stringent calibration procedures. A certified medical physicist calibrates the photon and electron beams according to the AAPM TG-51 protocol or TRS 430 to ensure that the machine's output accurately matches the prescribed treatment doses (Brittany Bird, 2024). This step is

crucial for maintaining safety and delivering treatments as intended. By adhering to rigorous quality control and conducting routine LINAC calibration, healthcare facilities can uphold high standards of radiation therapy treatment and ensure the safety and well-being of patients undergoing radiation treatment.

2.4 Treatment planning system (TPS)

A TPS is a sophisticated computer software that calculates the optimal beam configurations, energies, field widths, and fluence pattern to provide a safe and effective dose distribution (Oncology Medical Physics, 2019). The primary functions of a TPS include lesion localization, where the exact position of the tumor within the body is identified, creation of radiation plans based on safety and health constraints, and the optimization of these plans to ensure they are geometrically feasible. Some of the well-known TPS available in the market include Philips Pinnacle (Philips, Netherlands) TPS, Varian's Eclipse (Varian, USA) TPS, Elekta's Monaco and XiO TPS (Elekta, Sweden), and RaySearch RayStation TPS (RaySearch, Sweden) (Radiology Oncology Systems, 2023).

2.4.1 Algorithm in TPS

TPS algorithms employ various methods to calculate radiation dosage. Diverse dose calculation techniques exist, encompassing kernel-based dosage algorithms, Boltzmann Transport dose algorithms, and Monte Carlo dose computation algorithms as illustrated in Figure 2.5 (Oncology Medical Physics, 2019). Kernel-based methods use models like pencil beam or more advanced ones like convolution to predict how radiation deposits from a specific point. Boltzmann Transport algorithms analyze how radiation moves through materials, and Monte Carlo algorithms use random simulations to find numerical solutions.

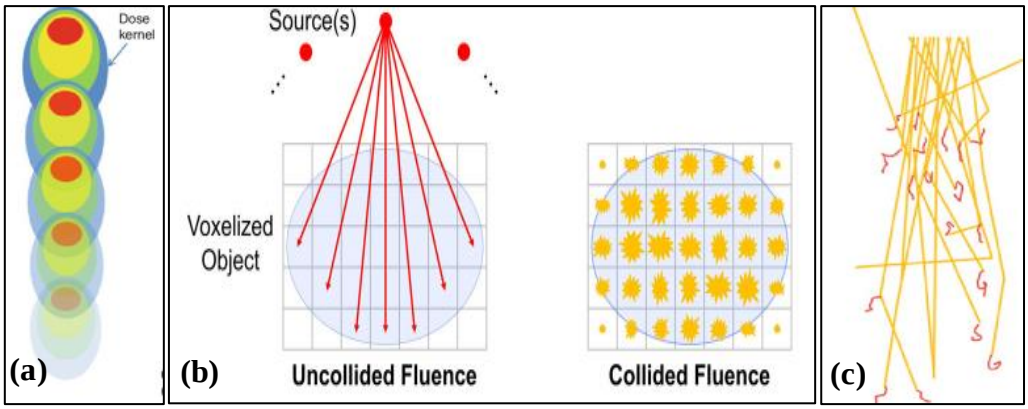

Figure 2.5: Dose calculation algorithm comparison (a) kernel-based method (Shibamoto *et al.*, 2015) (b) Boltzmann Transport dose algorithm (Wang *et al.*, 2018) (c) Monte Carlo method (Shibamoto *et al.*, 2015)

2.4.2 Algorithm used in Monaco

The Monaco TPS features advanced algorithms such as the Pencil Beam (PB) and Collapsed Cone Convolution (CCC) for radiation dose calculation in cancer treatment. In addition to the PB and CCC algorithm, The Monaco TPS enhances its accuracy with the integration of the MC algorithm, which generates dose predictions by considering secondary photons, electron scattering, and dose absorption, especially in scenarios involving tissue heterogeneities which varies in density and composition, from dense bone to light lung tissue. By using random numbers to model interaction probabilities, the MC algorithm ensures precise dose distributions tailored to the specific interactions within the treatment area. (Tugrul, 2021).

Monaco TPS features multiple dose calculation algorithms tailored for various radiation therapy planning needs. It utilizes the CCC algorithm is used for 3D CRT photon treatments Additionally, the X-ray Voxelized Monte Carlo (XVMC) algorithm for photon-based treatments in IMRT, VMAT, SRS, SBRT, and 3D CRT planning (Clements *et al.*, 2018).

2.4.3 Dose ccalculation algorithm and optimization system in Eclipse and Monaco TPS

Eclipse employs the AAA dose calculation while Monaco uses MC dose calculation for VMAT plans. Additionally, their optimization systems differ, complicating direct comparisons. In the AAA algorithm, inhomogeneity corrections are applied by anisotropically scaling the photon and electron scatter kernels based on the electronic density distribution of the irradiated medium. On the other hand, Monte Carlo algorithms account for both the primary radiation transport and the scatter within and around inhomogeneities, simulate the interactions of individual particles with the medium, providing highly accurate dose distributions(Zaman, Kakakhel, and Hussain, 2018). These differences can lead to variations in dose calculations, especially in complex or heterogeneous tissue scenarios (Snyder *et al.*, 2018).

Eclipse and Monaco TPS utilized distinct optimization methodologies and dose calculation algorithms, influencing how treatment plans are developed and the resulting dose distributions. According to Eldib *et al.* (2021), Monaco employs a range of biological and DVH functions during optimization. These include the Poisson statistical cell kill model, as well as serial and parallel complication models where they consider the biological response of tissues to radiation, which can lead to more clinically relevant dose distributions that prioritize tumour control while minimizing damage to healthy tissues , aimed at achieving optimal dose distributions for treatments like VMAT. Monaco's optimization process occurs in two stages: first, beam segmentation is determined, followed by dose optimization utilizing the Monte Carlo-based virtual source model. In contrast, Eclipse TPS primarily relies on dose volume objectives (DVO) for its optimization process. The DVO optimizer iteratively adjusts beam parameters to meet specified dose distribution goals efficiently. This approach prioritizes achieving desired dose volumes within OARs and target volumes.

2.4.4 Accuracy of algorithm in different medium

Precision in treatment planning and dose delivery is essential, especially in heterogeneous media. Aram *et al.* compared four dose calculation algorithms in both homogeneous and heterogeneous settings (Aram *et al.*, 2023). The study found that all algorithms had dose deviations within ±5% in heterogeneous media. Specifically, the CCC algorithm's passing rate was slightly below the target at 94% in these conditions (Aram *et al.*, 2023). This finding aligns with Chopra *et al.*'s research, which also highlighted similar accuracy issues in dose calculations in the presence of tissue heterogeneities (Chopra *et al.*, 2018).

2.5 Dosimetry verification in TPS

Verification of dosimetry in TPS is critical to ensuring the precision and reliability of radiation therapy protocols. Dosimetric testing involves confirming that the dose distribution and dose calculated by the TPS accurately matches the prescribed treatment plan. To ensure this accuracy, TPS must conduct dosimetric verifications using a variety of tools, including ionization chambers, diode detectors, film, and phantoms.

2.5.1 Dosimeters in radiotherapy

Dosimetry involves the scientific methods of measuring, calculating, and assessing radiation doses. Medical physicists use these processes to ensure that radiation delivery equipment is precisely calibrated and accurate. Radiation dosimetry converts the amount of ionizing radiation absorbed by tissues into a measurement reflecting its effect on those tissues (Greene *et al.*, 2018). Commonly used radiation dosimeters include ionization chambers, radiography films, TLDs, diodes, and metal-oxide-semiconductor field-effect transistors (MOSFETs), each chosen for specific applications due to their strengths and weaknesses. In this study, TLD and Gafchromic film are employed, with the Gafchromic

films used for relative dosimetry and TLDs for absolute dose and point dose measurements, as confirmed by Branco et al. (Branco *et al.*, 2017).

2.5.2 Principle of TLD and Gafchromic Film

A TLD measures ionizing radiation exposure, such as gamma rays, x-rays, and beta radiation, by quantifying the light emitted from a crystal within the device upon heating. When ionizing radiation hits the TLD, it energizes electrons within the crystal lattice, causing them to move to higher energy states and become trapped in lattice defects. During the readout process, the TLD is heated, allowing these trapped electrons to release their energy as they return to their ground state, emitting visible light. The intensity of this light, measured by a photomultiplier tube or similar device, is proportional to the radiation dose absorbed and is converted into a dose reading through calibration curves (Perkins, 2022).

Film dosimetry using Gafchromic films is essential for measuring dose distributions, crucial for quality assurance in TPS and linear accelerators. This technique is especially useful for verifying complex radiation therapy plans such as IMRT and VMAT (Dabrowski, Drozdyk, and Kulolowicz, 2018). Gafchromic film operates on the principle of colour change in response to ionizing radiation exposure, enabling accurate and visible dose mapping. The film contains layers of a polymer matrix with radiation-sensitive dyes that undergo a chemical reaction when exposed to radiation like X-rays or gamma rays. This reaction produces free radicals that trigger a polymerization process, darkening the film proportional to the radiation dose received. Analyzing the film's optical density (OD) changes through scanning and specialized software allows for precise dose mapping, calibrated against known doses for accuracy.

2.6 TPS Validation

The precision of dose calculations in a TPS is crucial, as it significantly influences the quality and success of patient treatments in radiation therapy. According to recommendations by the TRS report 430, various aspects of dosimetric TPS commissioning are essential, including the TPS's ability to replicate input data, algorithm verification, calculation verification, analysis of extreme cases, and comprehensive end-to-end testing (Oncology Medical Physics, 2019). Various scenarios such as irregular field shapes, heterogeneous materials like lung and bone, different source to surface distance (SSD)s, use of wedges, and multi leaf collimator (MLC) shaped fields were considered. This study, however, will focus on dosimetric verification through dose distribution and dose output calculations in environments featuring bone and soft tissues.

For validating dose calculation algorithms such as MC, ensure the absolute dose delivered to the patient or phantom is accurate. Measurements are taken using calibrated detectors, such as ionization chambers or thermoluminescent dosimeters, to determine the absolute dose., as outlined in TRS 430 (Smilowitz *et al.*, 2015). Measurements using any available heterogeneous phantom are recommended. Verification of dose distributions should include tests for complex scenarios like transitions between tissue-air-tissue, small field sizes, and irregular surfaces. However, due to the limits of this study, these complex scenario tests will not be included. The ICRU specifies that dose calculated by the TPS should not deviate from the measured dose by more than ±5%

2.6.1 Patient Specific Quality Assurance (QA)

Treatment planning precisely delivers radiation to target areas while protecting nearby organs at risk (OARs) using treatment techniques such as 3D-CRT and IMRT, using adjustable photon beam intensities controlled by an MLC. VMAT builds on IMRT by providing equally effective or superior dose distributions more efficiently, by adjusting

MLC positions, gantry rotation speeds, and dose rates simultaneously. VMAT is a complex treatment technique, which offers precise dose distributions with enhanced target coverage and reduced normal tissue exposure compared to 3D conformal radiotherapy. Its delivery involved intricate adjustments in MLC leaf positions, gantry rotation speed, and dose delivery rate, either through single or multiple arcs depending on treatment complexity (Low *et al.*, 2018).

However, excessive modulation in VMAT can create differences between planned and delivered doses, risking ineffective treatment. This occurs due to complications in dose calculations and mechanical operations. Highly modulated VMAT plans may use small or complex beam shapes that are difficult to calculate accurately, increasing dose calculation uncertainties (Park *et al.*, 2018). The intricate mechanical movements required for VMAT, involving MLCs, the gantry, and beam delivery systems, also introduce mechanical uncertainties, potentially leading to deviations from planned movements (Park *et al.*, 2018).

To address these issues, pre-treatment verification of VMAT plans using PSQA, especially gamma index analysis, is crucial and routinely performed to ensure accurate delivery.

2.6.2 Heterogeneous medium study

Various pretreatment patient-specific dosimetric quality assurance (QA) measures are employed in contemporary radiation therapy techniques to ensure the precision of treatment planning. While many studies have scrutinized algorithm research using a water equivalent phantom, there is a scarcity of investigations using a tissue equivalent phantom resembling the human body, especially in the context of the Monaco TPS. Taylan Tugrul (2021) conducted a study on the Monaco TPS algorithm, focusing on an esophageal case and the investigation revealed that the CCC and MC algorithms utilized in Monaco TPS

significantly influence dose distribution, particularly in regions with abrupt density changes (Tugrul,2021). These variations result in differences in doses absorbed by critical organs such as the lung and heart. Yadav *et al.,* observed significant variations in measured dosages of a phantom using Rapid Arc plans. For homogeneous phantom, there were minor differences between planned and measured doses across all rapid arc QA plans, indicated by a mean percentage variation of 1.4299 and a standard deviation of 0.768. However, this discrepancy was not statistically significant ($t = 0.00508$, $\rho = 0.497982 > 0.05$). Conversely, for the heterogeneous phantom, the mean percentage variation between planned and measured doses across all rapid arc QA plans was higher at 6.890, with a larger standard deviation of 2.565. This difference was found to be statistically significant ($t = 3.21604$, $p = 0.001063 < 0.05$). This underscores the significance of heterogeneous media in influencing dose estimations (Yadav *et al.*, 2023).

In a distinct study, Mamta Mahur *et al* utilized a heterogeneous head and neck phantom to evaluate Monaco TPS across various dose delivery techniques (VMAT, Segmental Simultaneous Integrated Modulated Radiation Therapy (SSIMRT) Dynamic Imagery-Guided Modulated Radiation Therapy (DIMRT), and 3DCRT). Their findings indicated differences between measured and calculated dose values ranging between 11.66% and 19.73%. These discrepancies align with the AAPM-TG 53 acceptance value of 20% for dose calculation in the buildup region by TPS (Mahur *et al.*, 2022).

2.6.3 Gamma index analysis

The gamma index serves as a valuable method for dosimetric validation, comparing the planned dose from TPS to the actual measured dose. It offers a quantitative measure of how well these doses agree (Das *et al.*, 2022). The gamma index method measures how well calculated and measured dose distributions match, using percent dose difference (DD) and distance to agreement (DTA). There are two approaches to calculating DD in

gamma index methods: global and local. The global gamma index evaluates DDs relative to the highest dose (or prescribed dose), whereas the local gamma index assesses DDs in relation to the doses at specific points being analyzed (Park *et al.*, 2018)

The gamma index γ is obtained by the renormalized criteria Γ using the following equation (Yusuke Anetai *et al.*, 2022):

$$\Gamma(r_e, r_r) = \sqrt{\frac{r^2(r_e, r_r)}{\Delta d^2} + \frac{\delta^2(r_e, r_r)}{\Delta D^2}} \qquad \text{Equation 2.1}$$

Where $\Gamma(r_e, r_r)$ is the distance between r_r and r_e, $\delta^2(r_e, r_r)$ is the DD between r_e and r_r and Δd^2represents the DTA criterion, and ΔD^2denotes the DD criterion.

In the DD criterion, percentage DD is typically normalized globally (divided by values like the prescribed dose per fraction or the maximum dose detected) or locally (divided by the dose at each specific position). Consequently, the gamma (γ) index meets these conditions.

$$\gamma(r_r) = min(\Gamma(r_e, r_r)) \wedge (r_e) \qquad \text{Equation 2.2}$$

The TG-218 report sets benchmarks for evaluating dose distributions in PSQA through the gamma index. It defines a universal tolerance limit with a 95% passing rate and a universal action limit with a 90% passing rate. Both limits require a 3% DD and a 2-mm DTA within a dose distribution threshold of 10% (Yusuke Anetai *et al.*, 2022). However, following to HUSM clinical practice, 3% DD with 3-mm DTA in the 10% threshold dose distribution and 95% gamma passing rate will be used.

CHAPTER 3 METHODOLOGY

3.1 Materials

This research was structured into two main phases: Phase I involved verifying dosimetry on a heterogeneous anthropomorphic RANDO Phantom using TLD-100 and EBT3 Gafchromic films. In phase II, consisted of the recreation of treatment plans from Eclipse TPS patient data on the Monaco TPS, followed by verification through PSQA using Arc CHECK phantom. All equipment used in this study was situated at the radiation therapy department in Hospital Universiti Sains Malaysia (HUSM), Kubang Kerian, Kelantan.

3.1.1 Dosimeters calibration materials

Prior to using the dosimeters for measurements, calibration was essential as accurate radiation dosimetry relies on the use of properly calibrated dosimeters.

3.1.1(a) Thermoluminescent Dosimeter chips (TLD-100)

The TLD-100 chips (Thermo Fisher Scientific, Massachusetts, United States) use lithium fluoride doped with magnesium and titanium (LiF: Mg, Ti). They are widely used in radiation therapy dosimetry because they closely resemble human tissue (with a Z value of 8.2, compared to Z_{tissue} 7.4), have minimal signal loss over time (5%-10% per year), can detect a wide range of radiation doses (10 mGy-10 Gy) with a linear response, and are highly sensitive. These chips can measure doses from various types of radiation, including photons (energy >5 keV), electrons (energy >70 keV), and neutrons, with a repeatability of 2% or better. Moreover, they show uniformity of ± 15% from sample to sample. For this study, TLD chips measuring 3.2 mm × 3.2 mm× 0.89 mm as shown in Figure 3.1 were used for dose verification purposes.

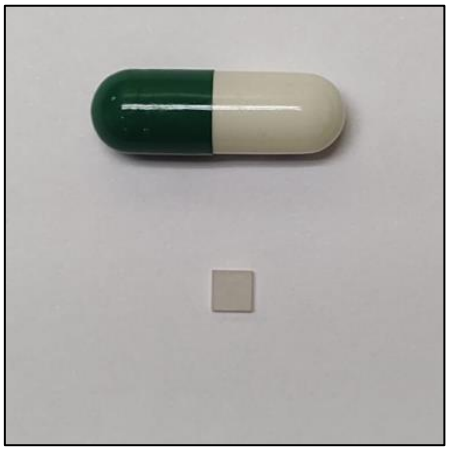

Figure 3.1: TLD-100 chips with dimension 3.2 mm × 3.2 mm × 0.89 mm

3.1.1(b) TLD Programmable Annealing Oven

Table 3.1: Specifications of TLD programmable annealing oven

Properties	Specifications
Housing	Stainless steel
Temperature range	Max 400ºC
Capacity (one cycle)	360 elements with standard trays
Chamber size	10 mm x 16.5 mm x 15.5 mm
Dimensions	440 mm x 420 mm x 330 mm

The TLD programmable annealing oven (RadPro, Germany) (model PTWT1321/U100) in the Medical Radiation Lab, USM as shown in Figure 3.2, is designed specifically for thermoluminescent dosimetry and is controlled by a programmable microprocessor. The specifications were stated in Table 3.1. It uses a heating element and fan to circulate hot air, ensuring uniform temperature distribution and avoiding thermal gradient issues. Automatic programs with heating and cooling

phases reduce errors from inconsistent annealing. The manufacturer provides a stainless-steel annealing tray for TLD elements.

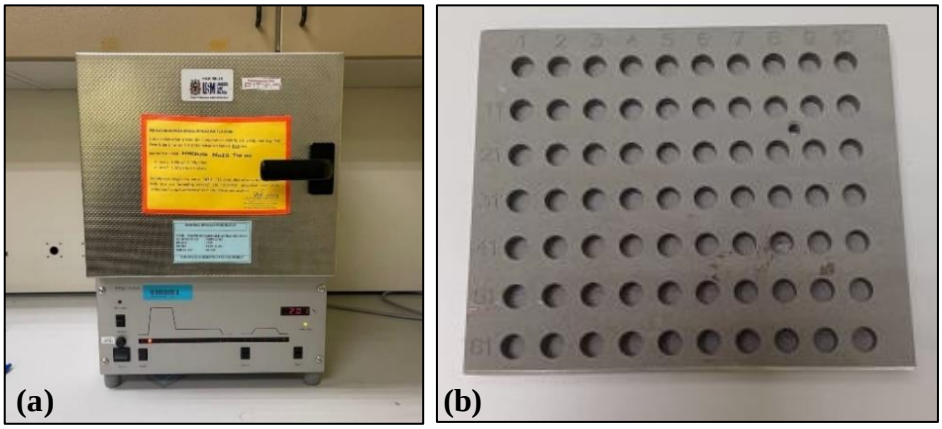

Figure 3.2: (a) TLD programmable annealing oven in USM (b) annealing tray for TLD elements

3.1.1(c) Harshaw TLD reader

The HARSHAW TLD Model 3500 Manual Reader (Thermo Fisher Scientific, Massachusetts, United States) as shown in Figure 3.3, is a compact device measuring 31 cm × 32 cm × 47 cm. It offers manual readout capabilities for thermoluminescence (TL) chips, disks, rods, and cubes in various sizes. The reader includes a tray specifically designed to securely accommodate a single-element TL detector as illustrated in figure 3.6, with each detector typically processed in approximately 30 seconds. Its heating system allows for linear programming adjustments to ensure precise readings, while a cooled photomultiplier tube and its electronics reliably detect and measure TL light emissions. The Thermo Scientific WinREMS software (version PL-26732.8.1.0.0) (Saint-Gobain Crystals & Detectors, USA) serves as the interface for reading TLD data, hosting the essential application software required for this purpose.