PATIENT-SPECIFIC QUALITY ASSURANCE FOR VOLUMETRIC MODULATED ARC THERAPY (VMAT) USING FLUENCE MAP ANALYSIS GENERATED FROM LOG DATA

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by

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LIST OF ABBREVIATIONS

2D	Two dimensions
3D	three dimensional
3DCRT	Three-Dimensional Conformal Radiotherapy
a-Si	Amorphous Silicon
AAPM	American Association of Physicists in Medicine
ACMP	American of College of Medical Physics
CAT	Customer Acceptance Testing
CT	Computed Tomography
CTV	Clinical Tumour Volume
EBRT	External Beam Radiation Therapy
EPID	Electronic Portal Imaging Device
FPD	Flat Panel Detector
GTV	Gross Tumour Volume
CTV	Clinical Tumour Volume
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Unit and Measurements
IMRT	Intensity Modulated Radiation Therapy
ITV	Internal Target Volume
kV	Kilovoltage
linac	Linear Accelerator
MLCs	Multileaf Collimator
MRI	Magnetic Resonance imaging
MU	Monitor Unit
MV	Mega Voltage

OAR	Organ at Risk
PET	Positron Emission Tomography
PTV	Planning Target Volume
QAP	Quality Assurance Program
PSQA	Patient -Specific QA
RMS	Root Mean Square
SSD	Source to Surface Distance
TCP	Tumour Control Probability
NTCP	Normal Tissue Complication Probability
VMAT	Volumetric Arc Therapy

JAMINAN KUALITI KHUSUS PESAKIT UNTUK TERAPI ARKA BERMODULASI VOLUMTERIK(VMAT) MENGGUNAKAN ANALISA PETA FLUENS YANG DIJANA DARIPADA DATA LOG

ABSTRAK

Terapi Arka Volumetrik Termodulasi (VMAT) ialah sejenis Radioterapi Keamatan Termodulasi (IMRT) yang melibatkan pemberian parameter alur yang kompleks termasuk kolimat pelbagai lapisan dinamik (MLC) daripada linac. Penggunaan pengesan jenis susunatur telah menjadi kaedah standard bagi verifikasi ketepatan rawatan sebelum rawatan diberi kepada pesakit. Walaubagaimanapun, kaedah ini mempunyai limitasi dari segi peleraian ruang pengesan tersebut, dan kebolehan menilai prestasi MLC, dan juga cenderung kepada kesilapan jika kalibrasi dos dan persediaan pengesan tidak dilakukan dengan betul. Kajian ini menilai ketepatan kaedah digital yang mempunyai ruang peleraian tinggi untuk verifikasi rawatan VMAT. Data log yang diambil daripada linac Versa HD (Elekta ltd., Crawley, UK) ketika rawatan VMAT. Kesemua parameter rawatan dinamik termasuk unit monitor (MU), posisi MLC, posisi kolimator, sudut kolimator, dan sudut alur dirakam sebagai data log pada 4 Hz. Pemberian rawatan juga diukur pada masa sama menggunakan kebuk pengionan susunatur 2D Octavius 1500 (PTW, Freiburg, Germany) bersama EPID ketika pengukuran log data. Parameter diekstrak dan dianalisa menggunakan algoritma MATLAB (MathWorks, Natick, MA). Keputusan menunjukkan bahawa datalog dapat menjejak MLC dengan kejituan 1.0 mm pada kelajuan daripada 3.04 ke 3.40 cm/s. Pernilaian fluens yang dihasilkan daripada pemberian VMAT menggunakan datalog menunjukkan keputusan yang sama dengan pengesan kebuk susunatur 2D, dengan nilai purata kadar kelulusan gamma sebanyak 97.5% pada 3%/3 mm. Teknik data log

mendapat kelulusan gamma sebanyak 98.5%, berbanding 97.5% daripada pengesan kebuk susunatur 2D. Data log linac digital ini mempunyai asas kepada kaedah verifikasi masa-nyata yang penting dan boleh digunakan untuk verifikasi VMAT rutin.

PATIENT-SPECIFIC QUALITY ASSURANCE FOR VOLUMETRIC MODULATED ARC THERAPY (VMAT) USING FLUENCE MAP ANALYSIS GENERATED FROM LOG DATA

ABSTRACT

Volumetric Modulated Arc Therapy (VMAT) is an Intensity Modulated Radiotherapy (IMRT) treatment that involves the delivery of complex beam parameters including the dynamic multi-leaf collimators (MLC) from a linac. The use of a detector array has become a standard method to verify the treatment accuracy before the treatment planned is delivered to the patient. However, the method has limitations in terms of the detector's spatial resolution and capability to assess MLC performance, as well as its prone to error if dose calibration and detector setup are not correctly performed. This study aims to evaluate the accuracy of a high-resolution, digital method using linac log data for VMAT treatment verification. The log data was obtained from a Versa HD (Elekta ltd., Crawley, UK) linac during VMAT treatment. All the dynamic treatment parameters including monitor unit (MU), MLC position, collimator position, collimator angle, and beam angle were recorded at 4 Hz in the log data. The treatment delivery was also measured simultaneously using an Octavius 1500 2D ionisation chamber array (PTW, Freiburg, Germany) and Electronic Portal Imaging Device (EPID) during the log data measurements. The parameters were extracted and analysed using algorithms written in MATLAB (MathWorks, Natick, MA). The results demonstrated that the majority of MLC's position errors ranged from -3.4 mm to 6.4 mm. Although some of the errors exceeded the 3.5 mm tolerance value of the TG-142, the occurrence of these errors was low. However, the MLC's speed errors ranged from 30 mm/s to 34mm/s. Evaluation of the fluence generated for the VMAT delivery using

log data was shown to agree well with the planned dose distribution measured in the 2D array detector, with an average gamma pass rate of 97.5% at 3%/3 mm. In comparison, log data obtained a higher gamma pass rate of 98.5% at 3%/ 3 mm. The digital linac log data provides the basis for an essential high-resolution real-time verification tool that may be used for routine VMAT verification.

CHAPTER 1
INTRODUCTION

1.1 Background

According to the World Health Organization (WHO), cancer is the leading cause of mortality in the world, with approximately 13 million fatalities expected by 2022(Xia et al., 2022). Cancer is a genetic disease due to a mutation that causes uncontrolled cell growth to the point in which the cell can no longer accomplish its primary function and begins to divide without stopping, forming a solid tumour. The main differences between normal and malignant cells are shown in Figure 1.1. One significant distinction is that cancer cells are less specialised than normal cells that are programmed genetically to undergo cell death or apoptosis so that cells are never overabundant. Thecancerous cells have an abnormal number of chromosomes arranged in a disorganised manner that causes the cells to have uncontrollable growth and division.

Cancer has a variety of therapeutic methods. The three basic approaches are surgery, chemotherapy, and radiotherapy as shown in Figure1.2. Surgery is often combined with other treatments for malignancies such as radiotherapy and chemotherapy due to the spread of microscopic cancerous cells through the body (Lyman et al., 2015). Chemotherapy uses specific drugs to treat malignant tumours. Its primary aim isto target cells that divide faster than normal cells, eliminate all tumour cells, and preventthem from returning (Kajiyama et al., 2017). In some cases, it is used to prevent or reduce the spread of cancer cells (Dunleavy et al., 2009). For optimal effect, several treatment techniques are often used together to treat cancer. Radiation therapy deliversa high dose to the tumour to kill the cancer cells. This method and the advancement of thetechniques used will be elaborated on in section 1.2.

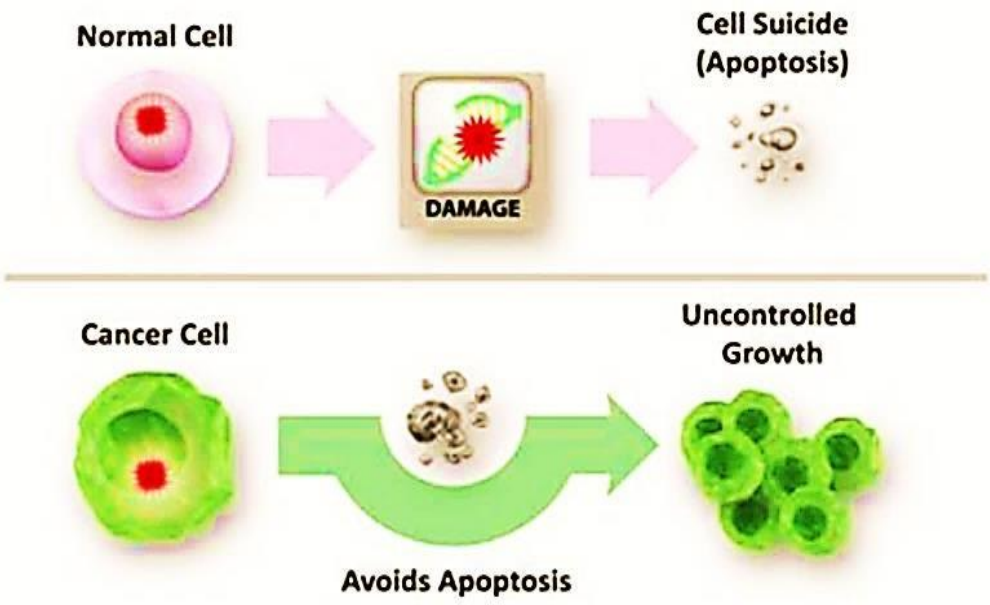

Figure 1.1 Healthy cells endure apoptosis whereas malignant cells avert apoptosis in uncontrolled numbers(Knowledge, 2014).

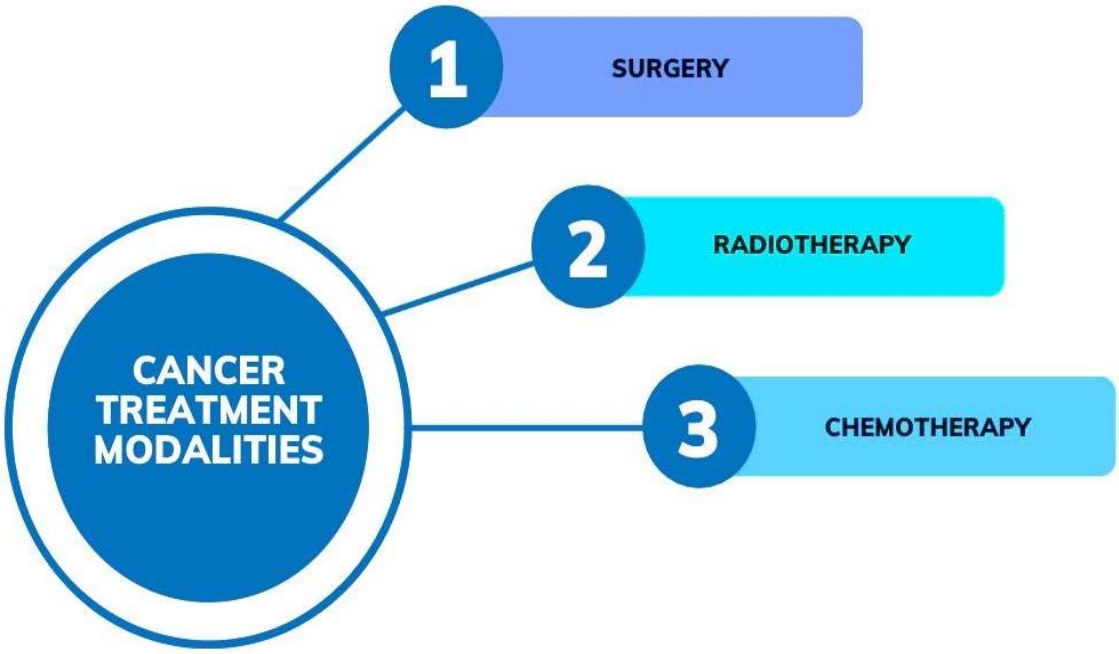

Figure 1.2 The three major cancer treatment modalities.

1.2 Introduction to modern radiotherapy

1.2.1 Principle of radiotherapy

Radiation is a physical agent that has been used for over 100 years to kill cancer cells. The radiation that is usually used is ionising as it produces ions and deposits high energy in solid malignant cells. This deposited ionised energy has the potential to destroy cancer cells or cause a genetic mutation that eventually led to cell death. The genetic material in cells, which is known as DNA, is broken by radiation, preventing them from dividing and proliferating further (B. J. Mijnheer et al.,2015). However, radiation can be both effective and potentially hazardous as it is unableto differentiate between healthy and malignant cells. The intrinsic goal of radiotherapyis targeting a specified volume of cancer cells with the maximum prescribed dose while sparing healthy cells in the path of radiation. The patient's cancerous cells will be eradicated during treatment, and this is accomplished in a variety of ways that differ depending on whether the radiation source is internal or external to the body(Murray &Lilley, 2019).

External beam radiation therapy (EBRT)is a radiation therapy method that involves directing well-localised high-energy rays(in the range of MV) from outside the body toward a targeted volume while minimising damage to healthy cells in the surrounding area using a linac(Mohamed, Ibrahim, Zidan, El-bahkiry, & El-sahragti, 2018).Whereas, internal radiation therapy, also known as brachytherapy, involves inserting a sealed radioactive source inside or near the region undergoing treatment(Murray & Lilley, 2019). It is most routinely utilised in the treatment of gynaecological and prostate cancers (Baskar, Lee, Yeo, & Yeoh, 2012). The relationship between therapeutic radiation dose and biological complications in normal and cancerous cells is the central focus of clinical radiotherapy. Tumour Control

Probability (TCP) is a parameter used to calculate the percentage of malignancies that are killed, whereas Normal Tissue Complication Probability (NTCP) curves define its effect on normal tissue damage as shown in Figure 1.3.TCP is represented by curve A, whereas NTCP is represented by curve B, and the therapeutic window is defined as the difference between TCP and NTCP. The therapeutic ratio is estimated from the expected gain in TCP to the risk of NTCP.

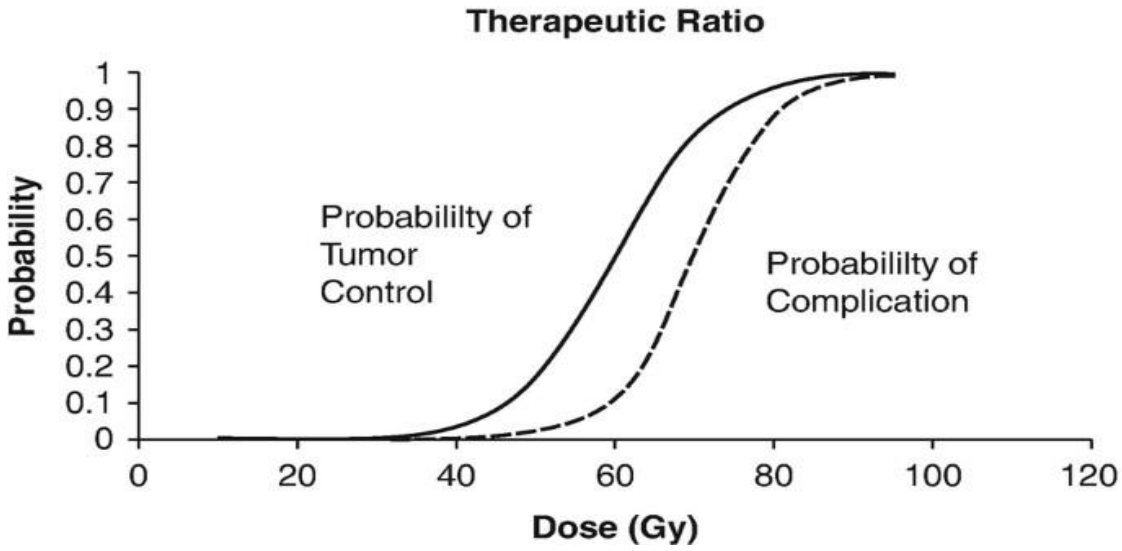

Figure 1.3 TCP is represented by curve A, NTCP is represented by curve B, andthe therapeutic window is represented by the blue-shaded region (Rosenberg, 2008).

For improving the quality of life, using radiation treatment techniques with the least quantity of toxicity is critical. Modern techniques of radiotherapy have been improved and employed in conjunction with advanced imaging modalities in clinical cases, sophisticated computer equipment with well-organised software, and delivery systems. This will be discussed in the subsequent sections.

1.2.2 Radiotherapy techniques

1.2.2(a) 3D conformal radiotherapy (3DCRT)

Rather than using two-dimensional (2D) radiation therapy based on a conventional radiotherapy simulator, three-dimensional (3D) radiation therapy is common nowadays. 3-D radiation therapy is based on computed tomography (CT) images that allow the visualisation of tumours and essential organ structures for optimum treatment planning, including beam placement (Baskar et al., 2012). Three-dimensional conformal radiotherapy (3D-CRT) uses a geometric field-shaping radiation beam based on 3D anatomic images of a patient's tumour and organs, along with accurate radiation dose distribution delivered to the tumour whilst minimising radiation received by the surrounding normal tissue(Zhao et al., 2021). A 3D-CRT treatment plan is created based on the number of beams, their shapes, intensities, and directions (for static fields). Computers calculate the dose distributions, and multi-leaf collimators shape the beams to conform to a tumor's shape. (Moustakis, Ebrahimi Tazehmahalleh, Elsayad, Fezeu, & Scobioala, 2020). Furthermore,3D-CRT generally uses 2-4 beams angled around the patient.

1.2.2(b) Intensity-modulated radiation therapy (IMRT)

IMRT is a sophisticated radiotherapy technique based on CT imaging that uses non-uniform intensity radiation beams assisted by multileaf collimator (MLC) movement during treatment. IMRT can create irregular-shaped radiation doses by setting multiple beams (often 5 -9) around the patient using inverse planning software to optimise the intensity-modulation of multiple beams during treatment. Each radiation beam is segmented into several beamlets with different intensities, providing multiform methods such as step-and-shoot and sliding window static modes that can be

used to treat patients. The resulting highly conformal dose distributions can be planned and delivered to the target with complex shapes to avoid essential structures (Rehman et al., 2019). A schematic illustration of an IMRT treatment is shown in Figure 1.4.

During the inverse treatment planning process, several inputs are given to the planning system to perform the calculations such as beam energy, beam direction, and restrictions of dose distribution in the tumour and organ at risk (OAR). The inverse planning algorithm generates the beam intensity and shape to fulfil the dose constraint. Optimisation techniques have been used for the determination of beam parameters such as beamlet weights to determine the treatment fields. As a result, inverse treatment planning is widely used to treat cancer patients in IMRT plans, as forwards planning is not able to the evaluation of beamlet weights(Rao & Chen, 2010).

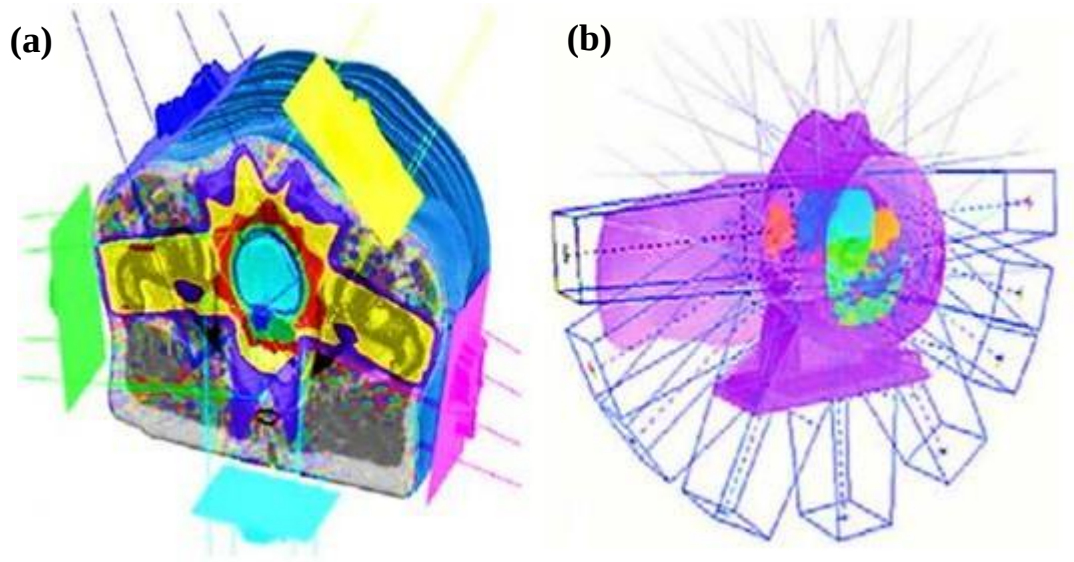

Figure 1.4 IMRT treatment conformality ; (a) prostate treatment (b) head and neck treatment(Nithiyanantham et al., 2015).

Volumetric Modulated Arc Therapy (VMAT) is a more advanced and complex type of IMRT. Rather than delivering radiotherapy from multiple static beam positions, the gantry angle rotates around the patient for a partial or full arc whilst delivering the

radiation beam, and the MLCs leave to move continuously to change the shape of the fields. VMAT can be considered as a combination of dynamic MLC modulation and gantry rotations (Herk & Ph, 1995). VMAT treatments have been used in clinical radiotherapy to enhance TCP by delivering a high dose to the tumour with better volume coverage while minimising NTCP (Rehman et al., 2019). VMAT technique has resulted in faster delivery with smaller monitor units (MUs), allowing for continuous dose rate, and gantry rotation speed changes to achieve a highly conformal dose (Erbakel et al., 2009). Many manufacturers have produced advanced MLCs with different MLC design features to achieve optimal dose distribution (Antypas, Floros, Rouchota, Armpilia, & Lyra, 2015; Ceylan, Inal, Senol, Yilmaz, & Sahin, 2021b). Figure 1.5 shows a schematic illustration of a sample VMAT treatment and Figure 1.6 shows an example of the dose distribution using 3D-CRT, IMRT, and VMAT for the same patient.

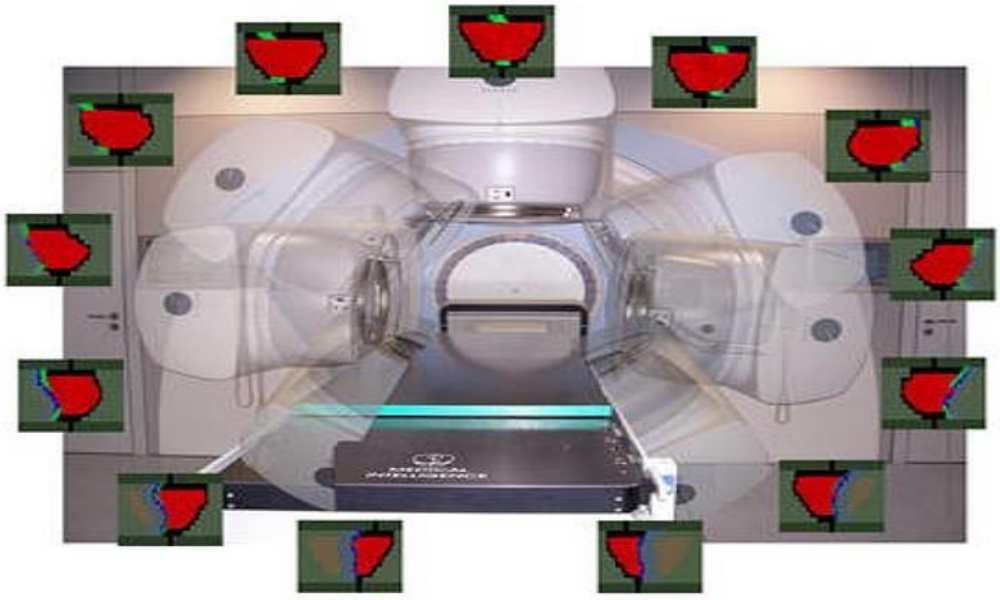

Figure 1.5 Schematic illustration of a sample VMAT treatment which shows the continuous change in the shape of the field during gantry rotation (Wolff et al., 2009)

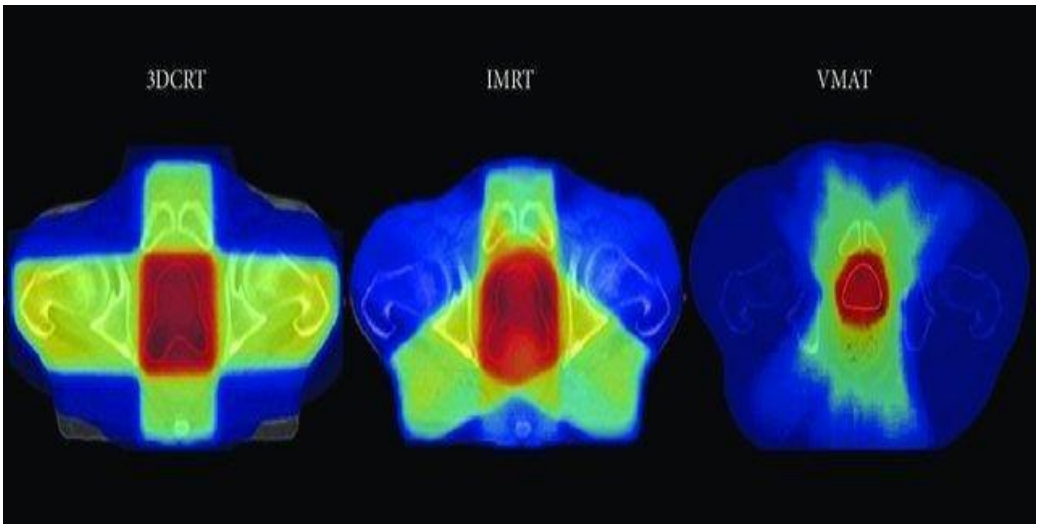

Figure 1.6 An example of the dose distribution using 3D-CRT, IMRT, and VMAT(Vanneste, Limbergen, Lin, Roermund, & Lambin, 2016).

1.3 Quality Assurance Program (QAP)

QA is a set of guidelines and protocols established to objectively evaluate the quality of treating patients. It is carried out by verifying that the device's mechanical and dosimetric characteristics are within an acceptable ranges of the baseline value, ensuring that patient treatment is provided within the prescribed dosimetric tolerances. Without the QA process, inaccurate radiation doses may be given to patientsdue to the negligence of output calibration (D I Thwaites et al., 2018).

Quality assurance in IMRT involves testing at least three different phases in the delivery process. Treatment planning and optimisation also need extensive and complicated testing. First, it is essential to guarantee that the delivery system is capable of delivering modulated beams with sufficient accuracy, taking into account the performance of MLC. This will be determined during the facility's initial commissioning and subsequent testing to confirm that the baseline performance is achieved. Second, it's critical to guarantee that the sequences or trajectories, along with the monitor unit calculations that comprise each patient's prescription, result in the

correct dose and dose distribution. This assurance is required before the patient is treated. Finally, in vivo measurements are widely recommended to ensure that the planned irradiation is given accurately(Williams, 2003).

Several professional organisations have issued guidelines for QA that should be followed. These organisations include the International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM. These guidelines use data provided by the International Commission on Radiological Protection (ICRP), and the International Commission on Radiation Units and Measurements (ICRU). Guidelines and recommendations of the treatment parameters set out by the American Association of Physicists in Medicine (AAPM)(Huq et al., 2016) and American College of Radiology and American College of Medical Physics in various documents in radiation oncology quality assurance reports(Avigo, Mignogna, & Linslata, 2018).

The AAPM task group TG-142 had two main changes (Klein et al., 2009). First to update the recommendations of AAPM TG-40 to cover modern linac technologies such as asymmetric jaws, MLC, and dynamic/virtual wedge (D I Thwaites et al.,2010). The TG-142 report provides a brief QA program guideline and a frequency of QA testing (Lim & Zin, 2017). Whilst the AAPM TG-218 provides a comprehensive report intended to improve understanding and reliability of these procedures, and even some recommendations for methodologies and tolerance limits are aimed at improving the PSQA (Bedford, Thomas, & Smyth, 2013).

1.3.1 Patient-Specific QA (PSQA)

The increasing complexity of radiotherapy delivery planned using the inverse optimisation method requires highly accurate verification techniques of the treatment delivery of dynamic variation of field shape, dose rate, and gantry speed. PSQA procedure is critical to ensure that the planned dose delivered to the patients is the same as prescribed in the VMAT or IMRT plans (Chendi et al., 2021).

PSQA procedure usually involves recalculating the dose distribution on the phantom. This method is performed using a detector system that is connected to a water-equivalent phantom. There are recommended measurement techniques, tools, and dose analysis methods in AAPM TG 119 and TG 218 to provide a systematic guidance for PSQA (Aapm, 2009; Miften et al., 2018). The dose distribution can be measured using various methods, such as a film, anion chamber, EPID, and a diode array detector. A gamma analysis is commonly used to compare the planned and the measured dose distributions (W.Ali et al., 2021; Jaafar et al., 2021). his metric is commonly used to calculate a quantitative measure of the spatial and dose criteria. The action and tolerance levels of gamma analysis are typically shown in terms of the distance to an agreement and thepercentage dose difference (Aapm, 2009; Katsuta, Kadoya, Fujita, Shimizu, & Matsunaga, 2016).

MLC performance is a critical aspect of the PSQA since increasingly complicated plans have been delivered with the MLC shape, gantry speed, and dose rate changing during treatment in single or multiple gantry rotations (Connor & Greer, 2012). PSQA has been used to guarantee that the delivered dose to the patient was the same as what physicists had planned. It is also intended to detect inconsistencies if the device is physically incapable of delivering the prescribed dose or is calibrated wrongly.

PSQA is a routine procedure that involves the replacement of a patient with a dosimeter. The final dose distribution is then compared to the desired outcome.

This thesis will discuss PSQA and evaluate the MLC performance using log data. Understanding the dynamics of MLC is also critical in determining the optimal treatment parameter output for a complex treatment delivery (Defoor, Vazquez-quino, Mavroidis, Papanikolaou, & Stathakis, 2015; Li, Chen, Zhu, Wang, & Liu, 2017a).

1.3.2 PSQA methods

PSQA can be performed with a broad variety of detectors(B. Mijnheer, Beddar, Izewska, & Reft, 2013; Zwan et al., 2016). Since linac was first utilised for EBRT, point measurements were mostly used. In sophisticated dose distributions with high dose gradients, such as IMRT, simple point measurements are insufficient for dose verification. Thermoluminescent dosimeter (TLD) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET) were used in one-dimensional (1D) measurements. This was partially overcome by using 2D dose measurements with radiographic films (Pai et al., 2007). Film measurements enable the verification of a 2D plane. Due to the limitations of film measurement, the dose evaluation process is often time-consuming and inefficient. The use of 3D detectors, such as solid plastic dosimetry and gel, has been shown to improve the efficiency of the procedure (Vandecastele, Sint-lucas, & Deene, 2013), These methods are helpful in the verification of 3DS doses, but they can be time-consuming and challenging for clinical use.

Two common popular detector types being used in the clinic for PSQA are EPID and detector arrays. Several studies have examined the use of EPIDs for capturing real-time MLC positions and reconstructing delivered doses. The EPID gives information on leaf position errors but does not extensive data for identifying delivery problems due

to its small panel size and low image resolution (Defoor et al., 2017). On the other hand, a 2D detector array system may provide an array of doses, but it suffers from low resolution. Dosimetric discrepancies may be caused by inconsistencies in MLC that can't be measured directly with these systems, which must be evaluated. The use of log data for patient-specific QA provides MLC performance information and has been heavily investigated due to its high temporal and spatial resolution and convenience (Barnes et al., 2018)It also does not consume time and workload since it does not require a detector setup (Pasler, Hernandez, Jornet, & Clark, 2018b).

For all of these reasons, dynamic log files have been suggested as a tool that can be utilised for patient-specific QA (Series, 2019; R. Wang et al., 2020). The use of this technique allows for the evaluation of multi-variable errors. It is very time-efficient and can be performed on a variety of errors using the Varian and Elekta linac (Calvo-ortega, Teke, Moragues, & Pozo, 2014; Defoor, Vazquez-Quino, Mavroidis, Papanikolaou, & Stathakis, 2015; Hughes, 2015). Most of the studies on utilising dynamic log files have previously been performed using Varian linac (Defoor, Vazquez-quino, et al., 2015),(Calvo-ortega et al., 2014; Hughes, 2015; Ibrahim, Mohamed, & Zidan, 2018; Kerns, Childress, & Kry, 2014; Ling et al., 2008; Slosarek, Szlag, Bekman, & Grzadziel, 2010). However, publications on patient-specific QA utilising log files for Elekta are scarce (Dobler et al., 2011; Haga et al., 2009; Q. Wang, Dai, & Zhang, 2013).Elekta file typically records the dynamic parameters of a given set of procedures every 0.25 s (Arumugam, Xing, Pagulayan, & Holloway, 2014; Picioli et al.,2019). The present work aims to evaluate the use of digital linac data for patient-specific QA for Elekta linac and verify the performance of Agility MLC.

1.4 Problem statement

There has been a paradigm shift in cancer treatment using more conformal radiation doses delivered using advanced radiotherapy techniques. Advanced radiotherapy treatments are getting more complicated in terms of planning and delivery so rigorous verification procedures are required before being delivered to the patient. Several studies show the importance of PSQA to evaluate the treatment before delivery as the probability of errors increases with increasing complexity. An accurate and robust PSQA program is required to verify the MLC performance as with any tools used in radiotherapy.

In this study, digital log data was utilised as a high-resolution real-time verification, useful in accessing accurate delivery of complex high-energy radiation to the tumour and ultimately to achieve better cure rates for cancer patients. The log data method is suited for routine PSQA, it is suitable for verifying the MLC performance within the acceptable tolerance. Additionally, the generated fluence map was compared in both log data and EPID to verify MLC performance. As well, the gamma passing rate was calculated using a 2D ion chamber array and log data. The PSQA created in this study is predicted to be able to be used as a routine program, reducing workloads by using a simpler QAP procedure whilst still increasing the confidence of VMAT treatment delivery.

1.5 Objectives of the study

The main objective of the study is to develop a digital method using fluence map from log data for routine PSQA for VMAT. Sub-objectives are as follows:

- To measure the MLCs errors during the VMAT deliveries.
- To evaluate the accuracy of the fluence map from the linac log data for VMAT PSQA.
- To compare the fluence map with EPID measurement and 2D array detector using gamma analysis.

CHAPTER 2
LITERATURE REVIEW

2.1 Radiotherapy flow

The treatment flow for a patient begins with the decision made by an oncologist regarding the type of tumour and its position. This step is carried out by using various imaging techniques such as computed tomography (CT) scanners, magnetic resonance imaging (MRI), and positron emission tomography (PET) to determine the tumour position. These imaging modalities provide three-dimensional (3D) anatomical information about the patient. Then, the oncologist uses CT images to determine the tumour delineation, while the physicist sets the radiation beams to cover the specified target. There are three main sub-volumes to define the tumour in radiotherapy planning, including gross tumour volume (GTV), clinical target volume (CTV), and planning target volume (PTV), as illustrated in Figure 2.1. GTV is the gross or visible extent of malignant growth and location. CTV contains a demonstrable GTV, plus a marginal spread of the subclinical microscopic malignant disease that cannot be fully imaged. PTV is a geometrical concept that defines the appropriate beam sizes and configurations and considers the net effect of overall potential geometric changes. It is constructed to ensure that the radiotherapy prescribed dosage is given to the CTV. Theorgans at risk (OARs) are the healthy tissues/organs located near the clinical target volume (CTV) whose irradiation may damage would alter the treatment plan(Frank, 2013).Before the treatment begins, the linac device and the patient are checked for QA.Then, the patient is placed on a portable treatment couch that can be moved in any direction. An immobilisation system, such as a thermoplastic mask, is usually utilised to fix the patient in an accurate position. The dose is delivered to the tumour while preserving the surrounding normal cells as the beams exit a specialised linac device

called gantry angle, which is rotated around the patient to deliver the dose from any angle by rotating the angle and moving the treatment couch. A brief radiotherapy workflow is shown in Figure 2.2.

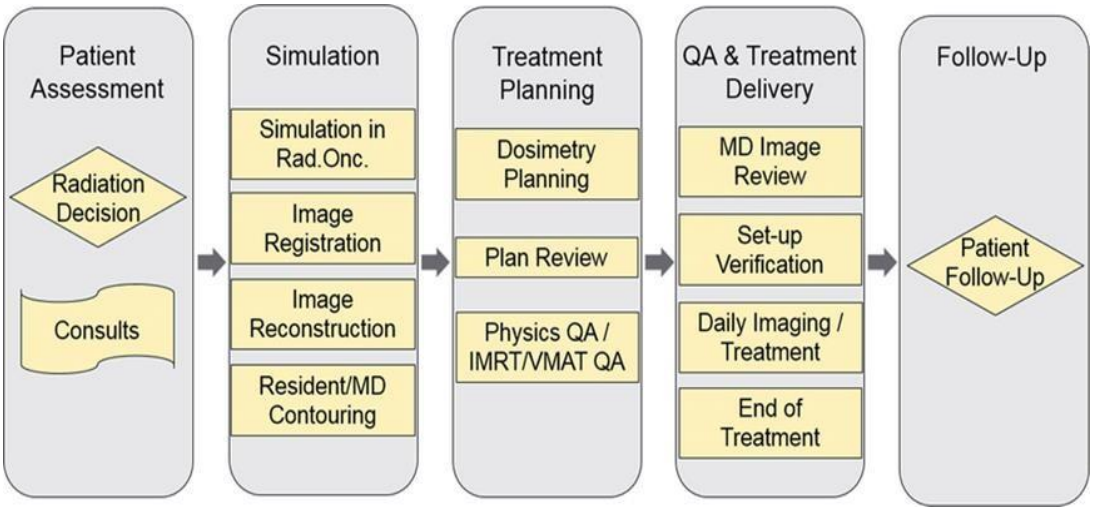

Figure 2.1The workflow of radiotherapy processes (Bossuyt et al., 2022)

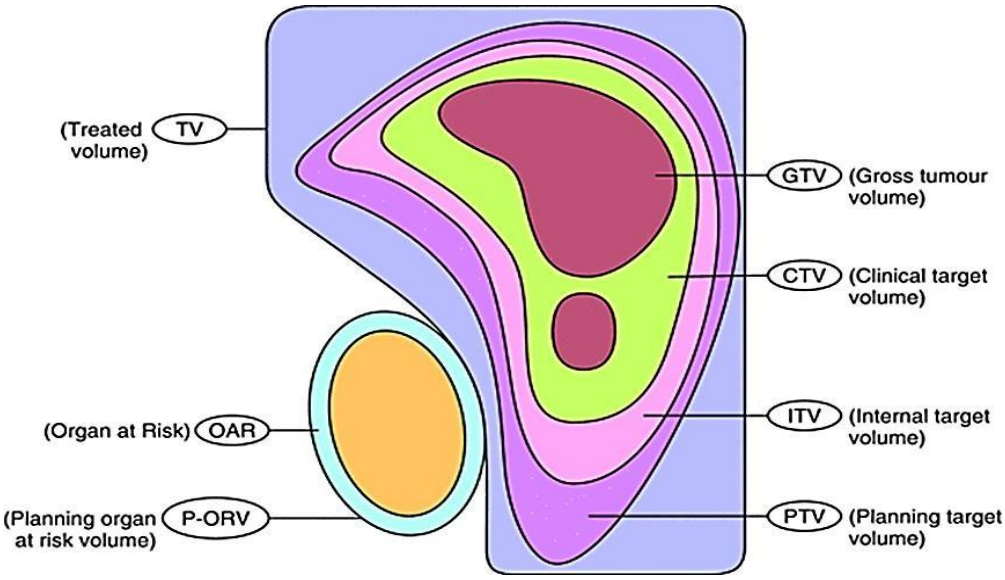

Figure 2.2 The main radiotherapy planning volumes taken from ICRU Report 50 (Mukherji, 2018).

2.1.1 Radiotherapy accidents and errors

Errors in radiotherapy can occur, and the effects on patients undergoing treatment can be severe. One of the goals of radiotherapy quality assurance is to provide a high level of accuracy of treatment delivery. Unfortunately, there are various factors that can contribute to the errors and limit the accuracy of the treatment. In recent years, several radiotherapy accidents were reported, as they highlight several fundamental challenges associated with avoiding, analysing, and learning from errors, particularly in the context of the medicolegal system (Esmati, 2022).

An "error" is any deviation between the provided numerical value of a quantity, such as a dose at a point or the position of a point, and its "true" value(Saito et al., 2018). Radiotherapy errors can be caused by a wide range of factors. These include human errors, mechanical or electrical issues, random errors, and systematic biases in the process. Human mistakes can be caused by inattention, while mechanical or electrical issues can impact the planning and delivery of radiotherapy. However,the conclusions from the accidents are connected to the frequency of direct and contributory variables and reveal that most of the accidents are caused by a lack of, non-application of, or underestimation of QA methods. Most of the potential accidents couldhave been averted if a comprehensive QA had been implemented correctly. The IAEA's planned international network for gathering additional lessons learned from different accidents may help many radiotherapy departments improve their clinical practice (Zhao et al., 2022).

Therefore, it is an essential requirement to provide an accurate system for radiotherapy verification to complement the existing planning and delivery systems. A broad range of essential suggestions has resulted from attempts to improve the

radiotherapy department's safety. Two main forms of verification have been established to ensure the delivery of the right dose geometric and dosimetric verification. Geometric verification verifies for position accuracy and ensures that the radiotherapy was delivered within the TPS limit uncertainty margin (M. A. Ali, Babaiah, Madhusudhan, & George, 2014). While dosimetric verification compares dose information collected by a detector during delivery to dose information generated by the dose calculation algorithm in the treatment planning system. This is done to ensure that the patient receives the correct dose within the specified dose tolerance. For patients receiving radiotherapy, a treatment plan should be thoroughly evaluated before the first treatment to ensure that the dose is accurate.

2.2 Linac

2.2.1 Basic overview

Linac is gaining significant ground in EBRT devices used to deliver prescribed doses to tumour cells. Linac uses high radiofrequency (RF) electromagnet waves to accelerate charged particles (electrons) to high energies in a linear pathway inside a tube called the accelerator waveguide, enabling these electrons to collide with heavy metals. The high-energy x-rays produced from the collision are then collimated according to the shape of the patient's tumour. X-ray therapy is intended to target cancer cells by breaking up DNA in all cells inside the treatment area while remaining normal cells unharmed (Murray & Lilley, 2019). EBRT technique was performed with x-rays produced at voltages up to 300 kV until the 1950s. In the 1950s and 1960s, high-energy devices known as cobalt-60 units gradually replaced the 300 kV machines. Nowadays, radiotherapy utilises a megavoltage linac (Ma et al., 2021). Betatrons were employed for radiotherapy in the early 1950s.

Cobalt-60 machines dominated radiotherapy since their introduction in the 1950s, but linac took over in the 1970s and 1980s as advanced technology. Both linac and cobalt-60 machines are used for megavoltage radiotherapy since then. In comparison, linac has a far more complex design than cobalt-60 radiotherapy machines because of the use of computer logic and microprocessors in the control systems of linac components such as MLCs, high dose rate, dynamic wedge, asymmetric collimator jaws, and gantry rotation. Despite the advantages of linac over other technologies, such as cobalt-60 medical equipment, it still remains a vital component of radiotherapy armamentarium in developing nations due to its low maintenance and cost due to its low servicing and maintenance cost, lesser dependence on reliable electrical power, simplicity of design, and ease of operation.

During the historical decades, the linac progressed through several advancements, as the early stage was shown in 1952 with an 8 MV x-ray beam linac that is bulky and has limited gantry motion. The second generation was designed between 1962 and 1982 with iso-centric units, rotating 360 degrees around the gantry axis and strengthening dose precision and accuracy. The third generation considered better accelerator waveguide and bending magnet systems and more beam-modifying accessories to provide a wide range of beam energy, dose rate, field size, and optimised beam characteristics of high reliability and computer-driven performance (David I Thwaites & Tuohy, 2006). Furthermore, radiotherapy contains several types of therapy, and it is commonly delivered in the form of x-rays or electrons. The radiotherapy dose is prescribed in Gray (Gy), representing the amount of energy deposited in the tissues(Murray & Lilley, 2019; Svajdova & Kazda, 2020).

Linac is divided into two main parts: external and internal components as shown in Figure 2.3**.** External components contain the treatment head anda stand that connects

the gantry (mounted on a linac) to the floor of the treatment room. The major internal components are magnetron or klystron. As a high-power oscillator, the magnetron generates several microseconds of 3GHz microwave pulses. In comparison, the klystron acts as a microwave amplifier. Magnetrons are cheaper than klystrons have a more extended period, generate higher power levels, and are preferred for beam energy above 20 MeV. As high-energy electrons emerge from the existing window of the accelerator structure, they are in a narrow pencil beam form. linac has relatively short accelerator tubes with 6 MeV or more energies, permitting electrons on a straight trajectory to enter the treatment head. In higher-energy linac, a longer accelerator tube is typically positioned perpendicular to the treatment head axis, and electrons are deflected by 90 (or 270) degrees using bending magnets (Haga et al., 2009). The head of treatment is the main segment of a linac. It generally includes a target, scatters foil, primary and secondary collimation system, flattening filter, ionisation chamber monitoring, and supplemental beam modification devices in some instances (Zhdanov & Dorosinsky, 2018). Three dynamic components of a beam collimation system are mainly defined as a rectangular-shaped radiation field, and MLC for refined beam shaping and beam fluence modulation (Surendran, Rao, & Lilly, 2014). MLCs are considered one of the most critical parts of linac and the significance of MLCs will be highlighted in section 2.2.2. Also, linac has advantages, including an opportunity to deliver very high energies without the need for exceedingly high voltage and provide higher doses than other machines (David I Thwaites & Tuohy, 2006).

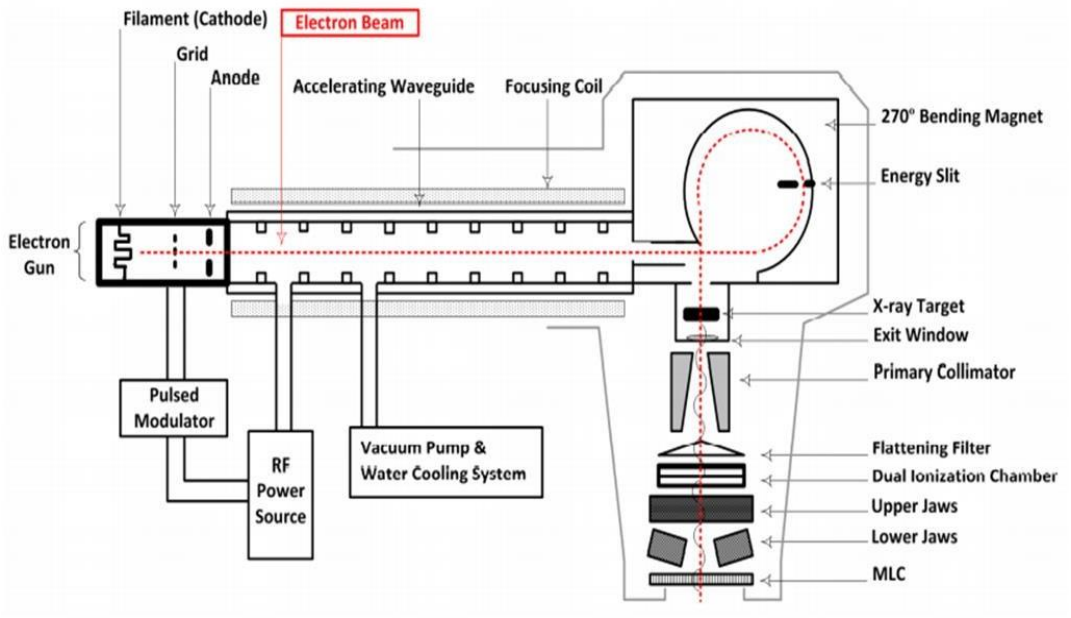

Figure 2.3 A schematic diagram of the medical linac components(Farzad, 2012).

2.2.2 Dynamic MLC-based radiotherapy treatment.

IMRT technique provides a much better dose distribution than 3D-CRT as discussed in section 1.2.2. Despite the novelty of the techniques, delivering 100% of the dose to the tumour and 0% to OAR is still impossible. As well as, two physical variables that should be optimised are the number of beams and the intensity map (Karagoz, Zorlu, Yeginer, Yildiz, & Ozyigit, 2016). The number of beams and angles are determined by the prescribed dose, tumour anatomy, and tolerance. A specific MLC configuration was used to generate the intensity map. As shown in Figure 2.4 each MLC configuration was known as a segment.

In advanced TPS, accurate MLC sequences are required for dose calculation. The MLC position sequences algorithm in TPS will generate a correct MLC sequence after optimising the dose. The delivery of IMRT can be performed in one of the main methods: dynamic or step-and-shoot MLCs (Karagoz et al., 2016).

In static MLC (sMLC) delivery, the treatment was given by several fields, and each field is subdivided into a series of subfields of radiation received with uniform

beam intensity levels of various shapes as shown in Figure 2.5. The multiple static MLC segments create the subfields and deliver them one by one in a stack arrangement without the need for operator involvement. While the accelerator is switched off, the leaves start moving to shape the next subfield. The static field is simple to verify and needlessly complicated QA techniques because the MLC is static during treatment delivery. Other parameters like MLC speed do not affect accuracy. Despite this, sMLC requires a lengthier treatment time due to a beam hold-off time for the MLC to shift between each segment.

In a dynamic MLC (dMLC) delivery, the corresponding leaves sweep in opposite directions concurrently, each with a different speed as a function of time. The intensity modulated radiation dose is delivered by moving the MLC continuously. However, the MLCs are continuously modifying the shape without any beam hold-off in between. The aperture between the leaves remains open for differential intensity delivery to different points in the field. The dMLCs are computer-controlled to control and track the position and speed of leaves. The dMLC method is more complicated than the sMLC method. A complex intensity modulated dose pattern is produced. The dMLC beam requires higher monitor units (MU) and a more comprehensive range of MLC speeds than sMLC (Li, Chen, Zhu, Wang, & Liu, 2017b).

VMAT is a more sophisticated radiotherapy modality than IMRT. The variable of MLC position, dose rate, and gantry rotation velocity may indeed allow VMAT to achieve precise dose distribution. VMAT can maximise dose distribution, minimise dose to normal tissues, and reduce delivery time compared to IMRT(Rao & Chen, 2010). The radiation delivery becomes more complicated than IMRT due to the MLC and gantry's dynamic movement. The accuracy of gantry angle and speed have to be verified in VMAT. Moreover, the significance of QA methods has risen in line with the

advancement of technologies. Thus, PSQA is essential for securing that the dose calculated by TPS corresponds to the dose given to the patient in the treatment unit(Lee, 2020,Inan & Gul, 2020).

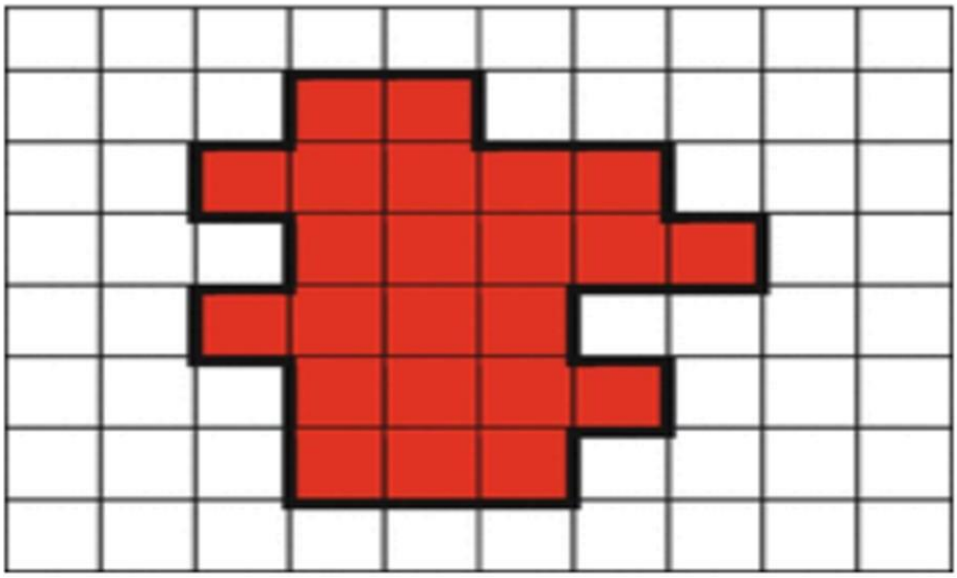

Figure 2.4 One segment of sMLC consists of 23 pixels(Samant, Parra, 2002).

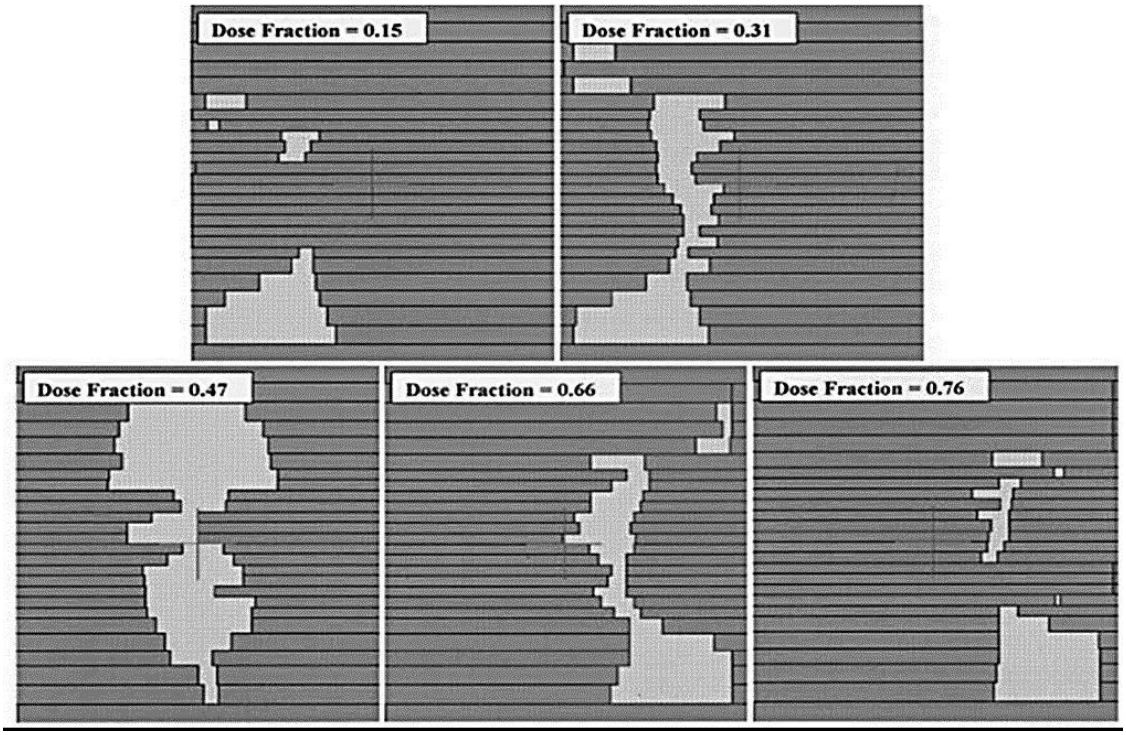

Figure 2.5 Five static MLC shapesdemonstrate the principles of using an sMLC for IMRT(Antypas et al., 2015).

2.2.2(a) Multi-leaf collimator (MLC)

In the 1960s, the invention of MLCs led to revolutionary developments in radiotherapy treatment. MLCs are a series of interleaved collimators in the gantry head used in almost every modern linac system; the number and thickness of the leaves vary depending on the vendor. MLC is divided into two banks of movable tungsten leaves that traditionally substitute the lead block in terms of beam collimation. Figure 2.6 shows the differences between conventional field shaping blocks and MLC systems (Christophides, Davies, & Fleckney, 2019.). Movable MLCs allow the generation of irregularly shaped radiation fields to conform to the shape of the target while minimising the irradiation of normal tissues. The shapes are provided by an array of narrow collimator leaf pairs, each monitored with its miniature motor (Hardcastle, 2020.; Hewson et al., 2020). The computer-controlled MLCs lead to more rapid field shape changes when multiple fields are applied(Losasso, Chui, & Ling, 1998).

MLCs are an essential radiotherapy dose distribution modification tool. Besides, it is crucial to monitor the mechanically complex features of an instrument that needs various distinct steps for implementation and continued use in the radiotherapy clinic. First, a series of acceptance tests for a new accelerator with MLC or an existing accelerator should be planned and carried out when the MLC reconfigures. Second, specific commissioning procedures are required to model the MLC for treatment(Kabat et al., 2019).

MLC is made of individual leaves of a high atomic numbered material usually tungsten that can move independently. MLC can move in a sequence of fixed positions during beam off(step-and-shoot) or moving continuously, allowing modulation of the dose fluence targeted at cancerous cells (dynamic MLC). Table 1shows the physical characteristic of two commercial MLC systems, Varian (Varian Medical System, Palo