WHOLE BRAIN RADIATION THERAPY VERIFICATION USING 2D GAMMA ANALYSIS METHOD

NIK NURUL AFINA BINTI WAN ZAINODIN

SCHOOL OF HEALTH SCIENCES

UNIVERSITI SAINS MALAYSIA

2020

WHOLE BRAIN RADIATION THERAPY VERIFICATION USING 2D GAMMA ANALYSIS METHOD

by

NIK NURUL AFINA BINTI WAN ZAINODIN

Dissertation submitted in partial fulfilment
of the requirements for the degree
of Bachelor of Health Science (Honours) (Medical Radiation)

August 2020

ACKNOWLEDGEMENT

All praises to Allah for His blessing in completing this dissertation project successfully. Special appreciations to my supervisor, Dr. Mohd Zahri bin Abdul Aziz, for his supervision and constant support. His help of guiding, constructive comment, supports and knowledge had contributed to the understanding in objectives of this study. Not forgotten, my appreciations to my co-supervisors, Dr. Jayapramila a/p Jayamani and Mr. Reduan bin Abdullah for their supportive comments, assistance regarding the flow of writing and in method handling. Sincere thanks to all my friends for their help and support throughout this project. Finally, my deepest gratitude goes to my parents, Nik Mas Wati binti Nik Mat and Wan Zainodin bin Wan Zakaria for their endless love, prayers and moral supports.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

׀ ׀	Absolute
°	Degree
γ	Gamma
<	Less than
≤	Less than or equal to
>	More than
%	Percentage

LIST OF ABBREVIATIONS

2D	2 dimensional
3D	3 dimensional
AAA	Anistropic Analytic Algorithm
C2	Cervical 2
CC	Collapsed Cone
CCC	Collapsed Cone Convolution
CRT	Conformal Radiotherapy
CT	Computed tomography
DD	Dose difference
DTA	Distance-to-agreement
FSPB	Finite-size Pencil Beam
HUSM	Hospital Universiti Sains Malaysia
ICRU	International Commission on Radiation Units and Measurements
IMRT	Intensity modulated radiotherapy
ISP	International Specialty Products
LINAC	Linear accelerator
MC	Monte Carlo
MU	Monitor Unit
MV	Megavoltage
OARs	Organs at risk
OD	Optical density
PB	Pencil Beam
PTV	Planning target volume
QA	Quality assurance
RTOG	Radiotion Therapy Oncology Group
SBRT	Stereotactic radiation therapy
SSD	Source-to-surface distance
START	Standardization of Breast Radiotherapy
TERMA	Total energy released in matter
TPS	Treatment planning system
VMAT	Volumetric modulated arc therapy

VMC+++	Voxel Monte Carlo
WBRT	Whole brain radiation therapy
XVMC	x-ray Voxel Monte Carlo

LIST OF APPENDICES

VERIFIKASI RAWATAN TERAPI SINARAN MENGGUNAKAN KAEDAH ANALISIS GAMA 2D

ABSTRAK

Radiasi terapi seluruh otak (WBRT) merupakan rawatan yang standard bagi pesakit dengan metastasis otak. Kecekapan algoritma pengiraan dos dan ketepatan penyampaian pelan rawatan kepada pesakit sangat penting dalam radioterapti. Dalam kajian ini, algoritma *Pencil Beam* (PB) dan *Collapsed Cone* (CC) dibandingkan untuk menilai impaknya terhadap pelan rawatan 3D-CRT WBRT. Selain itu, kajian ini bertujuan untuk mewujudkan satu prosedur jaminan mutu verifikasi pelan rawatan yang menggunakan filem EBT3 dalam fantom kepala takhomogen. Pelan rawatan 3DCRT WBRT yang dikira oleh algoritma PB dan CC dibandingkan dari segi dos kepada isipadu sasaran perancangan (PTV), dos kepada organ-organ berisiko (OARs) dan juga unit monitor (MU). Kadar peratusan lulus indeks gama juga dibandingkan untuk kedua-dua algoritma tersebut menggunakan perisian Verisoft. Dapatan kajian mendapati bahawa, algoritma PB memberikan dos purata dan dos maksima yang tinggi berbanding algoritma CC. Nilai MU yang dikira oleh algoritma PB ialah 420.26 MU dan kurang sebanyak 0.99% berbanding algoritma CC. Nilai-p yang didapati >0.05. Justeru itu, tiada perbezaan bererti antara peratusan lulus indeks gama bagi algoritma PB dan CC. Algoritma CC memberikan ketepatan gama yang lebih tinggi berbanding algoritma PB dengan nilai 87.25% bagi algoritma CC dan 79.98% bagi algorithma PB. Analisis indeks gama 2D digunakan sebagai salah satu pilihan untuk memastikan penyampaian dos yang lebih tepat kepada pesakit.

WHOLE BRAIN RADIATION THERAPY VERIFICATION USING 2D GAMMA ANALYSIS METHOD

ABSTRACT

Whole-brain radiation therapy (WBRT) is a standard radiotherapy treatment for the patients with multiple brain metastases. The efficiency of the dose calculation algorithm and the accuracy of the dose delivered to the patient is crucial in radiotherapy. In this study, Pencil Beam (PB) and Collapsed Cone (CC) algorithms in Oncentra Masterplan treatment planning system (TPS) were compared to assess their impact on the three-dimensional (3D) planning of the WBRT. Besides, this study aim is to establish a procedure of pre-treatment patient-specific quality assurance using EBT3 film in the heterogeneous anthropomorphic head phantom. A 3D conformal radiotherapy (CRT) of WBRT plans were constructed using both algorithms. The doses in the planning target volume (PTV), organs at risk (OAR) and monitor unit (MU) calculated by the algorithms were compared. Furthermore, the accuracy of both algorithms was evaluated using EBT3 film by comparing the gamma index passing rate in a Verisoft software. The comparison between the PB and CC algorithms in the TPS calculation showed that the dose distribution using the PB algorithm gave a higher maximum and mean dose to the PTV compared to the CC algorithm by 0.15% and 0.1%. However, the MU calculated by using the PB algorithm was 420.26 MU and it is lower than the CC algorithm by 0.99%. The p-value for this study was >0.05, which indicates that there is no significant difference between these two algorithms for the gamma index analysis. The CC algorithm showed a better accuracy than the PB algorithm since the measured dose in the film was closer to the calculated dose in the TPS with a higher gamma index passing rate than the PB algorithm. The CC algorithm gave the passing rate of 87.25% using 3 mm/3% (DTA/DD)

method than PB algorithm with 79.95%. The 2D gamma index analysis using EBT3 film is suggested to practice as the pre-treatment patient specific quality assurance (QA) for the 3D-CRT WBRT plan.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Brain metastases are neoplasms that originate in tissues outside the brain and then spread to the brain secondarily (Patchell, 2003). The brain metastases are frequent intracranial neoplasms in adults and the frequency of occurrence varies from 10% to 15% in patients diagnosed with cancer. Most brain metastases are found in patients diagnosed with lung, breast cancer and melanoma (Suteu *et al.*, 2019). Whole-brain radiotherapy (WBRT) is palliative treatment for the patients with multiple brain metastases or presenting with an uncontrolled primary tumor or multiple extracerebral metastases (Gaspar *et al.*, 2000). The treatment volume should include the whole brain including olfactory groove and middle cranial fossa (Hoskin, 2019). The computed tomography (CT) images data acquired to enable the visualization of the treatment area and used for the dose calculation in the treatment planning system (TPS).

In routine clinical radiotherapy applications, calculations of the dose to the target are performed by commercial TPS. The majority of these systems utilize Pencil Beam (PB) and Collapsed Cone (CC) algorithms for the dose calculation (Zhao *et al.*, 2014). The PB algorithm is commonly used in the clinical practice because it is very fast, however it is well known that the PB algorithm has shortcomings in the inhomogeneity regions such as bone and lung where the charged particle equilibrium does not hold (Zhao *et al.*, 2014). Meanwhile, the CC algorithm produces values that are closer to the measured values than the PB algorithm (Koelbl *et al.*, 2004). However, the CC algorithm still deviates from the measurement by more than 5% under certain circumstances (Krieger and Sauer, 2005). This is still questionable for the dose calculations accuracy in the whole-brain treatments.

The accuracy of the dose calculation is important for the quality of the treatment planning and consequently, for the dose delivered to the patients undergoing radiotherapy. Hence, a pre-treatment patient-specific quality assurance (QA) is important to guarantee that the plan delivered is an accurate representation of the calculated plan in the TPS. The pre-treatment patient-specific QA is often performed on a QA phantom with dosimeters to get the measured dose. This measured dose distribution evaluated against the calculated dose distribution obtained from the TPS using gamma index parameter (Jiang *et al.*, 2006). This gamma index method evaluates the coincidence between the calculated and measured dose distributions by employing the dose difference (DD) and the distance-to-agreement (DTA) (Low *et al.*, 1998). There is a general agreement of the gamma index in a planar dosimetry that the actual delivered dose should be within 3 mm/3% (DTA/DD) and 90% acceptance level of the planned treatment plan (Siochi *et al.*, 2013).

1.2 Problem Statement

WBRT treatment requires megavoltage (MV) energy and if it is not properly planned in the TPS, it could lead to treatment errors that is hazardous to the patient (McTyre *et al.*, 2013). In clinical radiotherapy, TPS is used to plan the treatment and the dose calculation algorithm available in the TPS will calculate the dose distribution to the treatment region. The radiotherapy treatment plan is challenging and complex due to the target region geometry which requires high accuracy in calculating the patient dose (Verma *et al.*, 2016). The efficiency of the TPS is highly depends on the type of algorithm used (Murat *et al.*, 2019). Thus, the selection of the dose calculation algorithm is important to ensure accurate dose estimation to the tumour and the normal tissues.

Inaccuracies during treatment planning may cause tumour recurrence and treatment-related complications.

Besides, the brain region consists of many critical structures of different densities and has an irregular shape (Koksal *et al.*, 2018). A small error in the treatment delivery can lead to a negative consequences as tumours are often located in close proximity to sensitive normal tissues and critical organs (Malicki, 2012). Errors in treatment delivery cannot be detected and eliminated if the pre-treatment QA is not being employed in radiotherapy.

1.3 Significant of the Study

This study determines and quantify the dose delivery accuracy between the measured and the calculated dose for the WBRT. This study determines the selection of the dose calculation algorithm in the Oncentra MasterPlan TPS for better treatment delivery in the WBRT using 3 dimensional (3D) conformal radiotherapy (CRT) technique. Besides, the result will allow an application of the anthropomorphic phantom with the human geometry for the pre-treatment patient-specific QA verification using 2 dimensionl (2D) dosimeter tool. Hence, the WBRT treatment planning and the delivery can be practiced under minimal dose calculation error.

1.4 Aim of the Study

This study aim is to verify the accuracy of the WBRT treatment delivery by using a GafChromic EBT3 film as a dosimetric tool in the 2D gamma index analysis.

Specifically:

i. To compare the calculated dose distribution between the PB and CC dose calculation algorithms in the TPS.

ii. To analyse the measured dose distribution between the PB and CC dose calculation algorithms on the GafChromic EBT3 films.

iii. To validate the accuracy of the PB and CC dose calculation algorithms on the GafChromic EBT3 films in the WBRT using gamma index analyis.

iv. To establish a standard procedure of pre-treatment patient-specific QA using GafChromic EBT3 films in the whole brain using 3D-CRT treatment technique.

CHAPTER 2

LITERATURE REVIEW

2.1 Treatment Planning System

TPS is an important element in the radiation therapy to improve the treatment quality. The radiotherapy workflow includes the CT simulation which requires patient's 3D image data set to identify the treatment region. The CT images are the main source to plan the treatment in the TPS. Once the CT images are loaded into the TPS and the tumours are identified, this system assist the planner to develop a plan for each beam line route on how the linear accelerator (LINAC) deliver the radiation. This software also calculates the expected dose in the patient's tissues (Kalet and Austin-Seymour, 1997). The dose calculation is critical in the treatment planning and this process is being facilitated by dose calculation algorithms in the TPS.

2.1.1 Pencil Beam Algorithm

PB algorithm assumes that any collimated incident photon beam is a combination of groups of smaller and narrow "pencil beams". Each pencil beam has central axis rays that deposits an amount of dose on the patient differed with the intensity and spectrum of the beam. Each pencil beam has a small diameter on the patient's surface. The dose is deposited under the surface when the beams hit the surface, produce a definite spatial distribution and spread out to form a tear-drop or pear-shaped dose distribution referred to as pencil beam dose kernel or dose kernel as shown in Figure 2.1 (Carolan, 2010).

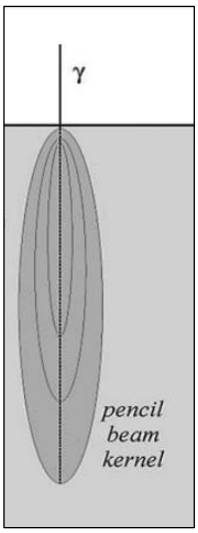

Figure 2.1: Pencil Beam dose kernel (Oelkfe and Scholz, 2006)

The dose distribution at each point from each adjacent pencil beams that involved in the whole beam is summed up to obtain the dose distribution for the whole radiotherapy dose. The patient's volume is divided into dose voxel and it is superimposed to the tabulated dose values for each pencil beam kernel. Thus, the dose contribution at each voxel in the volume by surrounding pencil beam adds up to obtain the total dose at that point by the superposition process. Figure 2.2 shows the summary flow chart on how the PB algorithm function. A fourier transform convolution can involve for the dose kernels that considered to be the same and the patient is considered to be in uniform density. However, different anatomical parts have different densities. The changes in density are utilized to modify the pattern of dose deposition for each pencil beam (Carolan, 2010).

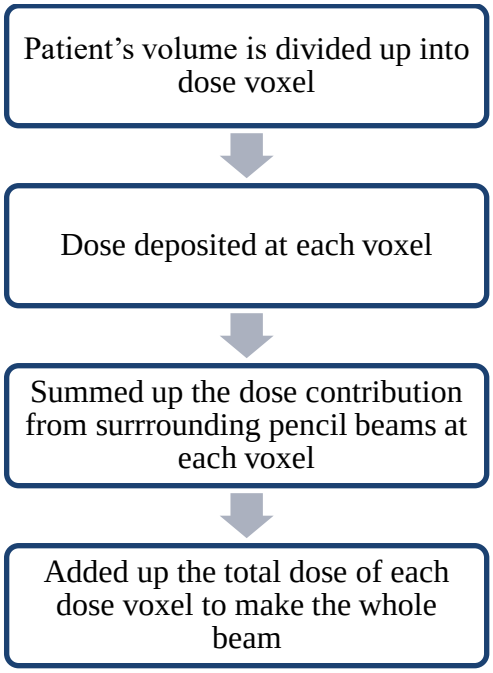

Figure 2.2: Summary of the PB algorithm workflow

2.1.2 Collapsed Cone Algorithm

The CC algorithm is one of the convolution/superposition algorithms used in the TPS. This algorithm was first introduced by Ahnesjo (Ahnesjö, 1989). This algorithm uses the input data principle from a beam model to calculate the dose for a radiation field. Beam model represents the radiation's characteristics exited from a LINAC and a combination of nominal energy. The radiation's characteristics compromised of the energy spectrum, output factors, profile definition, and geometric machine characteristics (Childress *et al.*, 2012).

When a photon beam radiates through the patient, the photons collide with the molecules of the patient. Some of the primary fluence energy is transferred to the patient and the algorithm calculates the primary 2D energy fluence from the radiation beam one field at a time. Primary energy fluence is the amount of incident photon energy upon a unit area calculated in a plane perpendicular to the irradiated beam. The energy fluence is projected across the patient model. After that, 3D total energy released in matter

(TERMA) is calculated. TERMA defines the amount of energy been released at a point. Finally, the TERMA is convoluted with the dose-spread function (kernel) to calculate the overall 3D dose distribution (Childress *et al.*, 2012). In this algorithm, the kernel is assumed to be divided into tens of collapsed cone that originate from the centric voxel with a TERMA value in all three spatial dimensions. Figure 2.3 shows the kernel values deposited along axis of each cone. Only the doses from the voxels that were transverse by axial lines in the collapsed cones are calculated and summed (Cho *et al.*, 2012).

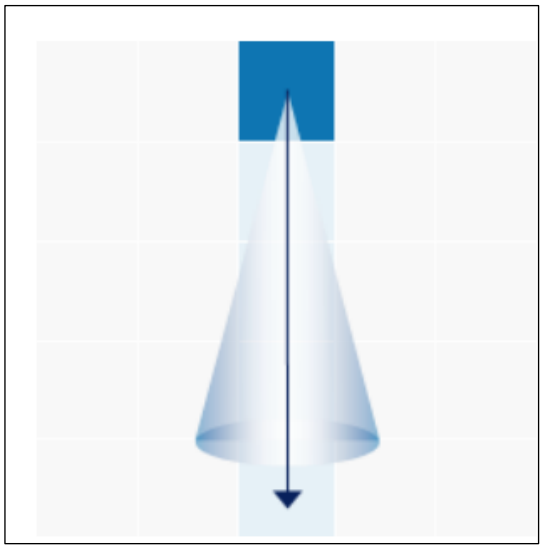

Figure 2.3: A TERMA voxel emitting a cone of energy. The only voxels that the dose is deposited to are along the collapsed ray line (arrow) (Childress *et al.*, 2012).

2.1.3 Dosimetric Analysis in the Treatment Planning System

Based on Irvine *et al*. (2004), a thirty PB treatment plans of lung and oesophageal treatments were recalculated using the CC algorithm, and plans were then compared and the monitor unit (MU) calculated by both algorithms were compared. A deviation present between the CC and PB algorithms by 3.4% when compared in term of MU required to deliver the prescribed dose.The dose distribution shown by the CC algorithm calculation was less homogeneous and the minimum dose to the target volume is less than the PB algorithm calculation. This raises the question of whether the prescribed dose should be

modified to account for more accurate absolute dose calculation. However, the CC algorithm has shown a better dose distribution in a low-density area and it is more preferred in the planning compared to PB algorithm where lung area is involved (Irvine *et al.*, 2004).

Krieger and Suer (2005) have conducted a study on evaluation of the accuracy of dose predicted in PB, CC and Monte Carlo (MC) algorithm in a heterogeneous medium using an ion chamber as a standard dose measurement. The heterogeneous medium is made up of a simple multi-layer phantom composed of Styrofoam and white polystyrene. Then, it was irradiated with 6 MV photon beam for the field size 10 cm × 10 cm and 20 cm × 20 cm respectively. The PB algorithm gave an overestimated dose of about 12% at the white polystyrene. In field size of 10 cm × 10 cm and 20 cm × 20 cm , the CC algorithm calculated 10% and 8% lower dose in the lower-density area than the MC algorithm. The PB algorithm did not consider the scattering geometry calculation when it is used to calculate the dose near the interface of different media and low-density region. The CC algorithm calculation used in an electronic disequilibrium area which is within the low-density region of the phantom contributes huge deviations for absolute dose (Krieger and Sauer, 2005).

Another study was conducted by comparing the anisotropic analytic algorithm (AAA) and CC algorithm to the voxel Monte Carlo (VMC++) treatment planning algorithms. Three lung and two breast clinical cases were selected for this study. The result of the study showed the overall performance of the CC algorithm is above AAA. However, AAA gave the shortest calculation time compared to the CC algorithm. The coverage of the target area shown a deviation of 0.4% for lung cases and -1.3% for breast cases for the CC algorithm. The deviation occurred due to individual patient

characteristics, size of the target volume and the beam arrangement (Hasenbalg *et al.*, 2007).

A study on the comparison of the PB, CC and MC algorithm in 6 MV photon radiotherapy treatment planning had been conducted by Kim *et al*. in 2015. The study was conducted on five patients on lung cases and another five patients on breast cases in which inhomogeneity area is demonstrated by both cases. This study has shown that the PB algorithm gives higher isodose coverage for planning target volume (PTV) in both breast and lung cases. However, the MC algorithm gives insufficient dose coverage in the lung cases. For breast cases, the PB algorithm showed a higher mean dose of the lung and heart, meanwhile, for the lung, the mean doses for the right lung and the heart were higher in the PB algorithm. MU calculation using the PB algorithm gives lower value compared to the CC and MC algorithms. It can be concluded that the PB algorithm gives less consideration in the change of density region and thus, overestimated the dose in the treatment planning system and underestimated the MU required to achieve dose coverage. Gamma analysis was also used to evaluate the dose distribution calculated by these three algorithms using a 3D diode array detector in a homogeneous QA phantom. The gamma passing rate was higher in the order of the PB, CC and MC algorithms. For the PB algorithm, the 3D gamma passing rate for the 3 mm/3% was 91.75 ± 9.12%, meanwhile for the CC and MC algorithms, the values were 93.12 ± 7.75% and 94.52 ± 5.85%. PB algorithm showed the lowest accuracy than the other algorithms. This is because the PB algorithm uses a one-dimensional density correction (Kim *et al.*, 2015).

Elcim *et al.* (2016) conducted a study on the dosimetric verification and comparative analysis of the treatment planning system of the CC and PB algorithms using Alderson RANDO Phantom. The study reveals that in the heterogeneous medium, the calculation of the PB and CC algorithms was comparable with the measured doses.

However, within interfaces, the difference between the measured doses and calculation done by the PB algorithm was higher than the CC algorithm. The measured dose for the CC algorithm was higher compared to the PB algorithm. The PB algorithm calculates a less absorbed dose than the CC algorithm in the interface of difference medium and irregular treatment regions. This is because the PB algorithm under estimate the lateral equilibrium's contribution to the total absorbed dose. Hence, dose calculation accuracy is limited especially in the heterogeneous mediums. In contrast, the CC algorithm can calculate both lateral and longitudinal electronic equilibrium while considering the scattered electrons. In heterogeneous medium, detailed source modelling and both primary and secondary interaction heterogeneity correction will allow a highly accurate calculation of absorbed dose (Kim *et al.*, 2015).

Li *et al*. (2018) conducted a study to evaluate the accuracy of the dose calculation in an intensity-modulated radiation therapy (IMRT) by comparing the dose calculated using a finite-size pencil beam (FSPB) and X-ray voxel Monte Carlo (XVMC) dose calculation algorithms. From the result, the average passing rates based on 3 mm/3% gamma criteria were 82.8 ± 1.0% and 96.4 ± 0.7% for FSPB and XVMC algorithm. This study concludes that the XVMC algorithm is more accurate in IMRT dose calculations with inhomogeneity correction than the FSPB algorithm. According to this study, the dose calculated in low-density tissues by the FSPB algorithm is higher than the measurements. FSPB is one of the algorithms in which the local dose distribution function or known as the kernel does not work accurately inside the lower density tissues such as the lung (Li *et al.*, 2018).

A study on the evaluation of the dose calculation accuracy of the TPS was conducted by Najafzadeh *et al.* (2019) using the Collapsed Cone Convolution (CCC) algorithm. The accuracy of the CCC algorithm was evaluated using a parallel-opposed

field in a lung phantom that consists of lung, soft tissue, spinal cord and bone. The CCC dose calculation accuracy was evaluated by using MC simulation and also to the dosimetric results measured by the Farmer chamber. Gamma index analysis also been done through the comparison of the MC simulation and the TPS calculated dose. The CCC algorithm underestimated the dose in the PTV by -0.11%, meanwhile in the right lung and lung-tissue interface regions, the dose was reduced by –1.6%, and –2.9% respectively. When compared to the MC simulation, the dose differences were –0.34%, –0.4% and –3.5%, respectively. The 3D gamma analysis results showed that the passing rates within the PTV and lung-tissue interface were above 59% and 76%. The gamma passing rates were above 80% for the right lung and spinal cord. This study showed that the CCC algorithm can calculate the dose with sufficient accuracy for 3D-CRT where a significant amount of tissue heterogeneity exists (Najafzadeh *et al.*, 2019).

2.2 Pre-treatment Patient Specific Quality Assurance

The dose distribution calculated by the TPS had to be verified before the treatment. There is an option in the TPS that permits exporting the radiation fields to a quality control phantom (Nalbant *et al.*, 2014). One of the method to verify the dose distribution calculated by a film dosimetry (Alber *et al.*, 2008). Dose fluence obtained from the TPS can be measured and evaluated using the gamma index analysis (Nalbant *et al.*, 2014).

2.2.1 Gamma Index Analysis

Gamma index is a calculation term that analysing the dose difference between the calculated and the measured dose distribution in radiotherapy treatment delivery. The main goal of gamma index analysis is to compare between the DD and DTA. The DD is the percentage difference between the measured and the calculated dose distribution which often shown as the percentage deviation from the calculated dose. The DD can be calculated by the ordinary subtraction of two images. As the DD is sensitive to steep dose gradients, therefore the DTA was developed. The DTA is the distance between a measured point and the nearest point in the calculated dose distribution that shows the same dose. The analysis was then performed for the low and high dose region (Low *et al.*, 1998).

Figure 2.4 showed an ellipsoid schematic illustration of the combined comparison. The surface of the ellipsoid is described by Equation 2.1 to 2.3 :

$$1 = \sqrt{\frac{r^2(\boldsymbol{r}_m, \boldsymbol{r})}{\Delta d^2{}_M} + \frac{\delta^2(\boldsymbol{r}_m, \boldsymbol{r})}{\Delta D^2{}_M}} \qquad \textit{(Eq. 2.1)}$$

where,

$$r\,(\boldsymbol{r}_m, \boldsymbol{r}) = |\boldsymbol{r} - \boldsymbol{r}_m| \qquad \textit{(Eq. 2.2)}$$

and

$$\delta\,(\boldsymbol{r}_m, \boldsymbol{r}) \;=\; D(\boldsymbol{r}) \;-\; D_m(\boldsymbol{r}_m) \qquad \textit{(Eq. 2.3)}$$

where $\delta\,(\boldsymbol{r}_m, \boldsymbol{r})$ is the dose difference at position $\boldsymbol{r}_m$.

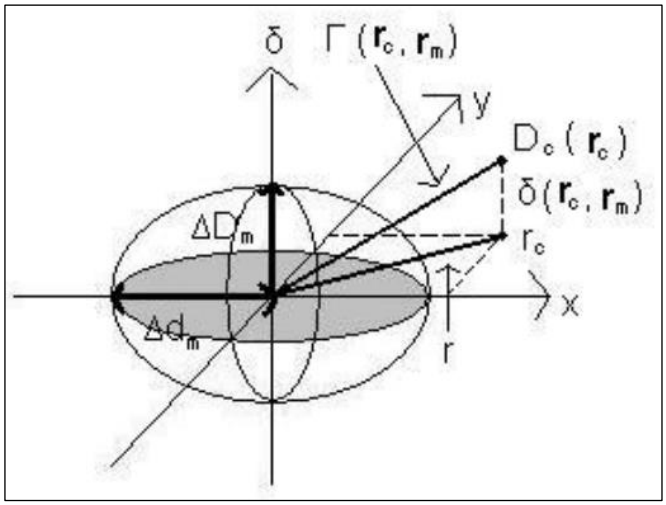

Figure 2.4: Schematic 2D representation of the combined gamma evaluation. The calculated dose distribution is denoted with *c* and the measured dose distribution is *m* (Low *et al.*, 1998).

The gamma (γ) function consists of an γ index and is given by Equation 2.4 to 2.7.

$$\gamma\,(\boldsymbol{r}_m) \;=\; min\,\{\Gamma\,(\boldsymbol{r}_m, \boldsymbol{r}_c)\}c\;\forall\{\boldsymbol{r}_c\} \qquad \textit{(Eq 2.4)}$$

where,

$$\Gamma\,(\boldsymbol{r}_m, \boldsymbol{r}_c) = \sqrt{\frac{r^{\,2}(\boldsymbol{r}_m, \boldsymbol{r})}{\Delta d^2{}_M} + \frac{\delta^2(\boldsymbol{r}_m, \boldsymbol{r})}{\Delta D^2{}_M}} \qquad \textit{(Eq 2.5)}$$

$$r\,(\boldsymbol{r}_m, \boldsymbol{r}) = |\boldsymbol{r} - \boldsymbol{r}_m| \qquad \textit{(Eq. 2.6)}$$

and

$$\delta\,(\boldsymbol{r}_m, \boldsymbol{r}_c) \;=\; D_c(\boldsymbol{r}_c) \;-\; D_m(\boldsymbol{r}_m) \qquad \textit{(Eq. 2.7)}$$

where δ ($\mathbf{r}_m$, $\mathbf{r}_c$) is the difference between the calculated and the measured dose distribution.

This gamma index method is used as a pass-fail criterion, where the calculation considered as passes if $\gamma(\mathbf{r}_m) \leq 1$ and failed if $\gamma(\mathbf{r}_m) > 1$. The gamma index is also used to discover dose deviation in 2D measurements (Low *et al.*, 1998).

2.2.2 EBT3 Film

GafChromic EBT film is a 2D dosimeter introduced as the first type of radiochromic film that is suitable for the use in the radiation therapy. The film was first released in year 2004 by International Specialty Products (ISP). In 2009, the GafChromic EBT film was replaced by the GafChromic EBT2 film. EBT2 film incorporates a yellow dye marker in the active layer and synthetic polymer as the biner component (Borca *et al.*, 2013). EBT2 film has a higher tolerance to light exposure than the EBT film and it can correct nonuniformity of the active layer thickness by using the yellow marker dye (Carrasco *et al.*, 2013).

In 2011, ISP released the GafChromic EBT3 film. The EBT3 film is designed for the measurement of the absorbed dose of ionizing radiation. This film particularly suitable for the high-energy photons (Borca *et al.*, 2013). The dynamic range of EBT3 film is in the dose range from 0.2 Gy to 10 Gy. The structure of EBT3 film is as shown in Figure 2.5. The film consists of an active layer with 28 μm thick and sandwiched between two 125 μm matte-polyester substrates (GafChromic, n.d.). This makes the film more robust and allows water immersion (Borca *et al.*, 2013). The active layer consists of the active component, a marker dye, stabilizers and other components that gives the film its near energy-independent response (GafChromic, n.d.). While the active layer composition and response is unchanged, one of the improvements of EBT3 film is the symmetric structure will avoid the potential errors in optical density measurements due to scanning side.

Besides, the matte polyester substrate will prevent Newton's Rings formation and the presence of fiducial marks that allows for the film automatic alignment (Borca *et al.*, 2013).

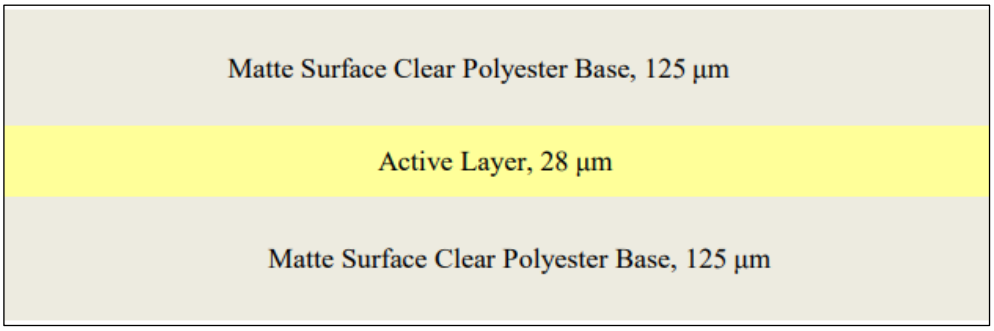

Figure 2.5: Structure of Gafchromic EBT3 film (GafChromic, n.d.)

The EBT3 film is a type of dosimeter based on the property of modifying the structural characteristic of their crystalline active component when being exposed to the ionizing radiations (Borca *et al.*, 2013). Interaction of the ionizing radiation with the film produces a polymerization process in the monomers of the active component. This microscopic phenomenon is reflected in the colour change at macroscopic level. Thus, the colour change of the film can be related to the radiation dose (Williams and Metcalfe, 2011).

EBT3 film presents many attractive characteristics as a dosimetric tool. It has high spatial resolution, weak energy dependence in a wide photon energy range, near tissue-equivalence, small dose rate and fractionation dependence and no angular dependence (Fuss *et al.*, 2007; Hermida-López *et al.*, 2014; Rink *et al.*, 2007). The detector also presents the advantage of easy handling, being self-developing and insensitive to room light, and offer the possibility of being dipped into water (Van Battum *et al.*, 2008). This EBT3 film can be digitized by using a flatbed charge-coupled device scanner equipped with a transparency unit for transmission measurements (Wilcox *et al.*, 2007). Today,

film dosimetry is a powerful tool in QA of the radiotherapy treatment quality assurance and it is a good method to verify the dose distribution (Devic, 2011; Falahati *et al.*, 2018).

2.2.3 EBT3 Film in Quality Assurance

A study to examine the dosimetric verification and quality assurance for the IMRT was conducted by Iqbal *et al.* (2018) using EBT3 film. 20 IMRT treatment plans were analysed that consist of 10 brain treatment plans and 10 prostate treatment plans. An ionisation chamber was used as a reference dosimetry. The gamma index passing rate complied about 95% at all different criteria which were at 2 mm/3%, 3 mm/3% and 3 mm/5% criteria. With the increasing tolerance, the gamma index passing rate also increases. This study suggested that the EBT3 film is reliable for the dose assessment and also as a IMRT quality assurance tool (Iqbal *et al.*, 2018).

Another study has been conducted by Stella *et al*. (2018) to optimize the procedures for volumetric modulated arc therapy (VMAT) and stereotactic radiation therapy (SBRT) patient-specific QA using EBT3 film. In this study, VMAT treatment plans were verified using an electronic portal imaging device of the ELEKTA LINAC and EBT3 film. The result of this study showed that the differences between the gamma index of EBT3 and EPID were less than 5% for the VMAT and SBRT plans. Hence, the use of EBT3 film dosimetry shows to be an accurate method for the VMAT conventionally fractionated and SBRT treatment plans verifications (Stella *et al.*, 2018).

Another study has been conducted in evaluating the accuracy of IMRT of lung cancer treatment planning using EBT3 films in a heterogeneous phantom. The EBT3 film was placed between the phantom and gamma passing rates with Gamma criteria of 3 mm/3%, 4 mm/4%, 5 mm/5%, 6 mm/6% and 7 mm/7% was used to compare between the treatment plan calculated dose and film measured dose. By increasing the gamma criteria, the gamma passing rates of the PTV and OARs also increases. The study concludes that

the usage of EBT3 film will allow the evaluation of the dose differences between the measured dose distribution and the calculated dose distribution in the TPS (Falahati *et al.*, 2018).

Abedi Firouzjah *et al.* (2019) conducted a study on the use of EBT3 film and Delta4 diode array for the dosimetric verification of the TPS. The study was conducted in a heterogeneous chest phantom using the IMRT technique. The gamma index differences between the film and Delta4 diode array was less than 5%. This study concluded there is a good agreement between the film and Delta4 as a quality assurance device (Abedi Firouzjah *et al.*, 2019).

CHAPTER 3

METHODOLOGY

3.1 Materials

The Oncentra MasterPlan TPS, GafChromic EBT3 film, EPSON Expression 1100xl Flatbed Scanner, Anthropomorphic RANDO phantom, solid water phantom and PTW Verisoft Software, Philips CT simulator and Siemens PRIMUS LINAC were used in this study. All the instruments used were located at Hospital Universiti Sains Malaysia (HUSM) and Medical Radiation Laboratory, School of Health Sciences USM Kubang Kerian Kelantan.

3.1.1 Oncentra MasterPlan Treatment Planning System

Oncentra Masterplan (Version 4.3) (Nucletron B.V., Veenendaal, Netherlands) TPS was used to plan and calculate for the 3D-CRT and brachytherapy. The dose calculation algorithms available in this system are PB and CC algorithms. The system utilises the volumetric information from the CT image data set that represents the patient anatomical structure for the dose calculation (Nucletron, n.d.). Figure 3.1 shows the interface of the Oncentra Masterplan treatment planning used in this study.

Figure 3.1: Oncentra MasterPlan Treatment Planning System

3.1.2 GafChromic EBT3 Dosimetry Film

In this study, GafChromic EBT3 (Ashland ISP, Wayne, New Jersey) film sheets with dimension of 20.3 cm x 25.4 cm (Lot #03071601) was used as a 2D dosimeter as shown in Figure 3.2. The EBT3 film used for measuring patient's dosimetry for the plan verification, over a dose range between 10 mGy and 40 Gy. This film features symmetrical structure and an anti-Newton's Ring coating. The spatial resolution for EBT3 film is 5000 dpi (GafChromic, n.d.).

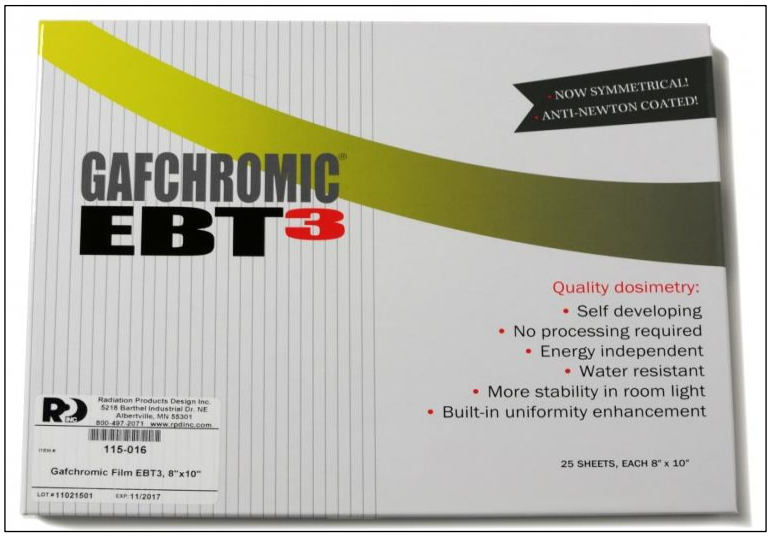

Figure 3.2: GafChromic EBT3 film

3.1.3 EPSON Expression 11000XL Flatbed Scanner

EPSON Expression 11000XL Flatbed Scanner (Epson Seiko Corp., Nagano, Japan) was used in this study as shown in Figure 3.3. The scanner is equipped with a transparency unit for transmission mode, which is the recommended mode for radiochromic films scanning (Desroches *et al.*, 2010). It can support a maximum size of A3 document (12.2" x 17.2") with a scanning resolution of 2400 dpi x 4800 dpi and optical density of 3.8 D. The scanner has a Xenon fluorescent lamp, a colour depth of 48-bit colour and grayscale depth of 16-bit. The specifications of this scanner described in Table 3.1 (Cnet, 2017).

Table 3.1: Specification of the EPSON Expression 11000XL Flatbed Scanner

Properties	Specification
Optical Resolution	2400 dpi x 4800 dpi
Grayscale Depth	16-bit (64K gray levels)
Colour Depth	48-bit colour
Lamp/Light Source Type	Xenon gas fluorescent lamp
Scan Density Range	3.8 D
Supported Document Type	Film, plain paper, slides, transparencies

Figure 3.3: EPSON Expression 11000XL Flatbed Scanner

3.1.4 Anthropomorphic RANDO Phantom

The RANDO phantom (Alderson Research Laboratories, New York, USA) as shown in Figure 3.4 is equivalent to the human body and designed following the International Commission on Radiation Units and Measurements (ICRU) 44 standards (Selwyn *et al.*, 2014). The phantom with length of 35 cm is transected-horizontally into 2.5 cm thick slices. The RANDO phantom used for this study consists of a head and neck region and filled with tissue-equivalent materials (Radiology Support Device, n.d.).

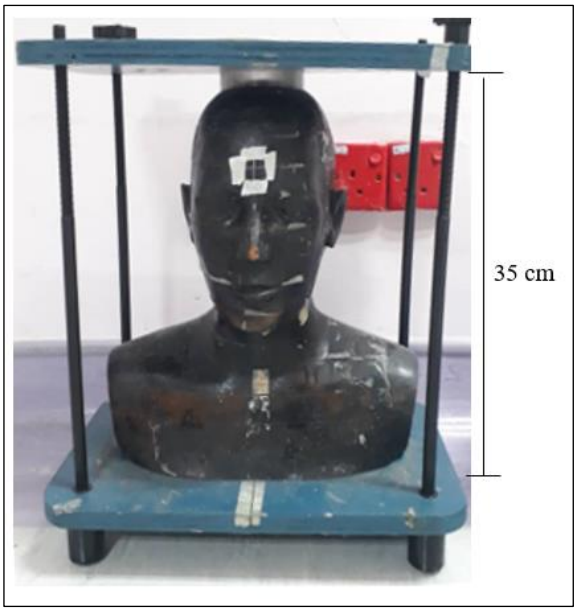

Figure 3.4: Anthropomorphic RANDO phantom, Radiotherapy Department, HUSM

3.1.5 Solid Water Phantom

The solid water phantom (PTW-Freiburg, Freiburg, Germany) as shown in Figure 3.5 is made up of water-equivalent RW3 material (Goettingen White Water). The mass density of the phantom is 1.045 gcm^{-3}. This phantom is used for calibration purposes and also QA measurements. The thickness of the slab of the solid water phantom varies from 1 mm to 10 mm thickness and each slab has a dimension of 30 cm x 30 cm (PTW-FreiburgGmbH, n.d.).

Figure 3.5: Solid Water phantom (PTW-FreiburgGmbH, n.d.)

3.1.6 Verisoft Software

Verisoft (version 5.1) (PTW-Freiburg, Freiburg, Germany) is a gamma analysis-based software used in radiotherapy for the treatment plans verification. The Verisoft enables the calculation of the 2D and 3D gamma index for three planes (axial, sagittal and coronal) and this may reduce the number of failed points in the high dose gradients. Figure 3.6 shows the interface of the Verisoft software. This software helps in locating the hot and cold spots and determine the maximum and average deviation of the calculated and measured plan (PTW-FreiburgGmbH, n.d.).

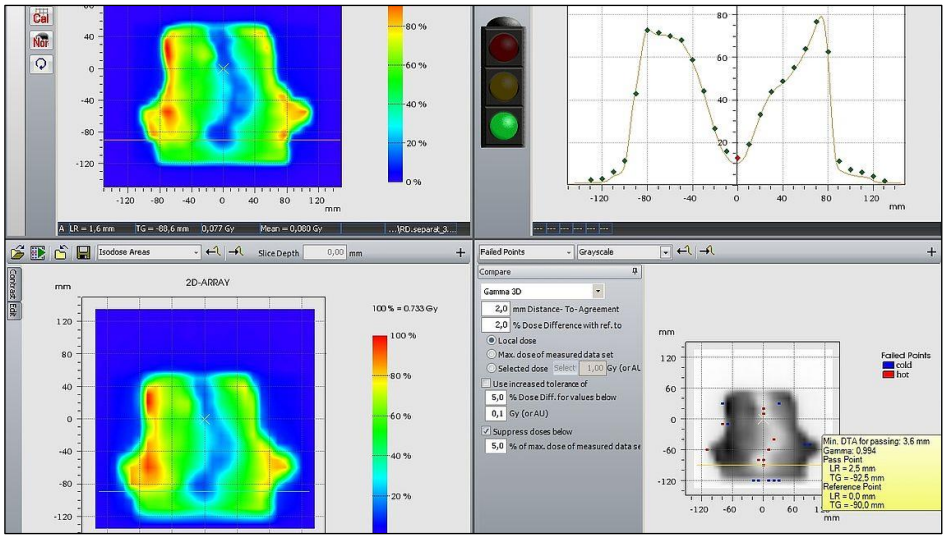

Figure 3.6: Interface of the Verisoft software (PTW-Freiburg GmbH, n.d.)

3.1.7 Philips Brilliance 16-Slice CT Simulator

The CT Simulator (Philips Medical System, Cleveland, US) featuring 60 cm scan field of view for full anatomic visualization as shown in Figure 3.7. The bore size of 80 cm provides the flexibility to position the patient. The simulator utilizes a 60 kW generator. The tube voltages available for this scanner are 90 kV, 120 kV and 140 kV (Philips, n.d.).

Figure 3.7: Philips CT Simulator, Radiotherapy Department, HUSM

3.1.8 Siemens PRIMUS Linear Accelerator

Irradiations were achieved by using a PRIMUS LINAC (Siemens Medical Systems, Concord, CA, USA) as shown in Figure 3.8. The LINAC has 58 multi-leaf collimator that replaced the lower jaw. Siemens PRIMUS is a klystron driven LINAC (Radiology Oncology Systems, n.d.). In Radiotherapy Department, HUSM, PRIMUS LINAC is being used for the 2D and 3D-CRT treatment approaches.

Figure 3.8: Siemens PRIMUS LINAC, Radiotherapy Department, HUSM