CHARACTERIZATION OF GAFCHROMIC HD-V2 FILM FOR DOSE VERIFICATION IN STEREOTACTIC RADIOSURGERY (SRS)

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RESEARCH REPORT SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MEDICAL PHYSICS

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ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Muhammad Taufiq Bin Azman

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Field of Study: Radiotherapy (Film Dosimetry)

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[CHARACTERIZATION OF GAFCHROMIC HD-V2 FILM FOR DOSE VERIFICATION IN STEREOTACTIC RADIOSURGERY (SRS)]

ABSTRACT

The purpose of this study was to characterize specific dosimetric properties of Gafchromic HD-V2 film and to investigate its feasibility in the dosimetric verification for Stereotactic Radiosurgery (SRS). Basic dosimeter properties including energy and dose rate dependencies were investigated and HD-V2 film showed energy and dose rate dependencies of less than 9.5% and 4.94% respectively. The HD-V2 film has very low dependency on scanning orientation in portrait versus landscape as well as "face-up" versus "face-down" scanning orientation. The percentage differences recorded were less than 2.7% for portrait versus landscape and less than 2.5% for "face-up" versus "face-down" orientation. In terms of angular dependency, there was no significant influence on net optical density, with deviations less than 4.3% for films irradiated at selected gantry angles ranging from 0° (which film is perpendicular to the irradiation beam) to 180°. Two treatment plans using SRS technique were created and irradiated using HD-V2 film for dosimetric verification. The dose distributions were calculated using a treatment planning system to obtain point doses at specified positions within a phantom. The calculated doses from TPS were compared to dose distributions delivered to HD-V2 film. The results of the point dose measurements for SRS treatment irradiations showed that the deviations between the TPS predicted dose and HD-V2 film measurements were less 4% which were within the recommended values by ICRU. This study shows that Gafchromic HD-V2 film can be used as dosimetric verification for SRS and for radiotherapy clinical practices that involves high range of doses of 10 to 1000 Gy.

Keywords: characterization, HD-V2 film, dose verification, SRS

[PENCIRIAN FILEM GAFKROMIK HD-V2 UNTUK TUJUAN PENENTUAN DOS BAGI TEKNIK RADIOSURGERI STEREOTAKTIK (SRS)]

ABSTRAK

Tujuan kajian ini adalah untuk mencirikan sifat filem Gafkromik HD-V2 dan dalam penentuan dos sinaran bagi teknik SRS menggunakan filem HD-V2. Ciri-ciri asas dosimeter yang digunakan dalam radioterapi termasuk kebergantungan terhadap tenaga dan kadar dos disiasat. Filem HD-V2 menunjukkan jurang kebergantungan terhadap tenaga dan kadar dos yang rendah dengan peratusan perbezaan bagi tenaga foton dan perbezaan kadar dos masing-masing adalah sebanyak 9.5% dan 4.94%. Filem HD-V2 juga mempunyai kebergantungan yang rendah pada orientasi pengimbasan filem seperti potret dengan landskap dan "permukaan menghadap" dengan" permukaan membelakangi" dengan perbezaan peratusan kurang dari 2.7% untuk potret dengan landskap dan kurang daripada 2.53% untuk "permukaan menghadap" dengan "permukaan membelakangi". Selain itu, kepadatan bersih optik terhadap kebergantungan orientasi sudut filem HD-V2 pada posisi dari 0° (filem yang berserenjang dengan sinaran) hingga 180° menunjukkan jumlah perbezaan yang kecil iaitu kurang daripada 4.3%. Dua pelan rawatan menggunakan teknik rawatan SRS klinikal telah dirancang dan disinar kepada filem HD-V2. Taburan dos telah dikira menggunakan TPS untuk mendapatkan taburan titik dos. Taburan titik dos yang dikira dari TPS dibandingkan dengan taburan titik dos pada filem HD-V2. Hasil perbandingan taburan titik dos TPS dengan filem HD-V2 bagi rawatan SRS menunjukkan perbezaan kurang daripada 4% dan dalam toleransi nilai piawai ICRU, IAEA dan AAPM. Hasil kajian menunjukkan bahawa filem HD-V2 boleh digunakan sebagai penentuan dos sinaran untuk teknik SRS dan juga untuk prosedur radioterapi klinikal lain yang melibatkan dos sinaran tinggi daripada 10 hingga 1000 Gy.

Kata Kunci: pencirian, filem HD-V2, penentuan dos, SRS

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LIST OF SYMBOLS AND ABBREVIATIONS

SRS	:	Stereotactic radiosurgery
OAR	:	Organ at risk
QA	:	Quality assurance
3DCRT	:	3D conformal radiotherapy
IMRT	:	Intensity modulated radiation therapy
VMAT	:	Volumetric modulated arc therapy
EBT	:	External beam therapy
MV	:	Megavoltage
MeV	:	Megaelectronvolt
Gy	:	Gray
SSD	:	Source surface distance
LINAC	:	Linear accelerator
IORT	:	Intraoperative radiotherapy
TLD	:	Thermoluminescence detector
MOSFET	:	Metal-oxide semiconductor field effect transistor
LiF	:	Lithium fluoride
CaF	:	Calcium fluoride
RGB	:	Red green blue
T	:	Transmission
OD	:	Optical density
CT	:	Computed Tomography
AAPM	:	American Association of Physicists
IVD	:	In vivo dosimetry
EBRT	:	External beam radiotherapy

TBI	:	Total body irradiation
RTQA	:	Radiotherapy quality assurance
MLC	:	Multi-leaf collimator
UMMC	:	University Malaya Medical Centre
d_{max}	:	Depth at maximum
TPS	:	treatment planning system
PTV	:	Planning target volume
PV	:	Pixel values
COV	:	Coefficient of variation
R^2	:	R-squared
SD	:	Standard deviation
RF	:	radiofrequency
CPE	:	charged particle equilibrium
ICRU	:	International Commission on Radiation Units and Measurements
IAEA	:	International Atomic Energy Agency
SBRT	:	Stereotactic Body Radiotherapy
Sv	:	Sievert

CHAPTER 1: INTRODUCTION

1.1 Research Background

Stereotactic radiosurgery (SRS) is one of the techniques used in radiotherapy for treatment of cranial cancers and certain benign conditions. SRS uses only one precisely focused radiation beam to treat tumour with volume usually less than 10 mm^3. The use of highly precise and accurate radiation beams in SRS is very important to deliver high levels of radiation dose to cranial region because it contains a lot of the organ at risk (OAR) in example brain. SRS targets require high dose of radiation between more than 10 Gy and less 100 Gy. In many situations, most of the treatment it can be higher than 10 Gy through one fraction to the affected area with minimal impact of high radiation dose to the surrounding healthy tissue. A precise delivery of SRS allows minimal damage to the healthy surrounding tissues. Stringent quality assurance (QA) and verification procedures with suitable dosimeter are required to ensure accurate dose delivery in SRS.

In clinical radiotherapy techniques such as 3D Conformal Radiotherapy (3DCRT), Intensity Modulated Radiation Therapy (IMRT), Volumetric Modulated Arc Therapy (VMAT) or Tomotherapy the gafchromic films are widely used in quality assurance and dosimetric verification. The gafchromic films that are usually used are the External Beam Therapy 3 (EBT3) film and HD-V2 film (Ashland, Kentucky United States). The characteristics and applications of Gafchromic EBT3 have been widely investigated and the results have shown that the films are capable to give reliable results for dose measurements with high degree of spatial accuracy.

The Gafchromic HD-V2 film is a relatively new type of radiochromic film that is meant for both dosimetry in megavoltage (MV) photon energy range and megaelectronvolt (MeV) electron energy range.

The HD-V2 film also has a dynamic dose range of approximately 10 Gy to 1000 Gy which meant for high dose applications. An active layer and an identical polyester layer product form an asymmetric configuration of the HD-V2 film.

Gafchromic HD-V2 is a radiochromic dosimetry film which is self-developing without the need for wet processing. Since it requires no post-exposure processing, there are no chemicals to dispose of and the film can be handled and used without need of a darkroom. The HD-V2 film possesses high potential for dosimetric verification in SRS technique. Before using this film for application in SRS dosimetry, its characteristics and limitations need to be investigated and well understood.

1.2 Importance of The Study

The film properties of HD-V2 film, as the newest film generation of Gafchromic film are important to be investigated. Since HD-V2 has different film structure and composition compared to HD-810 and EBT3, protocols for film dosimetry may be different from its predecessors.

Some features of SRS delivery such as small fields and high radiation dose requires certain form of dosimetric verification in order to deliver safe and precise radiation dose to the target area while minimise the radiation to the surrounding healthy tissues or organs. The Gafchromic HD-V2 film has a number of known advantages for dosimetric verification in SRS needs for example high spatial resolution, lower uncertainty associated to Gafchromic film dosimetry and suitability for absorbed dose of high-energy photons (10 Gy-1000Gy).

On top of these advantages, it is important to investigate other physical characteristics of the HD-V2 film and explore the possibility of using it in clinical practice, particularly for high dose treatments such as SRS delivery.

1.3 Objectives of The Study

1.3.1 Aim

To investigate the characteristics of Gafchromic HD-V2 film and its application for dosimetric verification in stereotactic radiotherapy (SRS).

1.3.2 Specific Objectives

i. Investigate the physical characteristics of HD-V2 film for radiation dosimetry & megavoltage photon energy range. Physical characteristics to be investigated are energy dependence, dose rate dependence, scanning orientation, post-irradiation development with time and angular dependence.

ii. To elucidate the feasibility of HD-V2 film in the dosimetric verification for stereotactic radiosurgery (SRS) delivery.

CHAPTER 2: LITERATURE REVIEW

2.1 Radiation Dosimetry

Based on (Whyte, 1973), the process of getting the value of the quantity experimentally using dosimetry systems is the measurement of a dosimetric quantity. The outcome of a measurement is the amount of a dosimetric quantity expressed as the product of a numerical value and an appropriate unit. Under radiation dosimetry contains health physics and radiation protection which are to measure, calculate and assess of the absorbed dose by the medium (human body) by ionizing radiation. This implement both internally, due to implanted, ingested or inhaled radioactive substances, or externally due to exposure from ionizing radiation by any sources of radiation.

A radiation dosimeter is a device, instrument or system that measures or evaluates, either directly or indirectly, the amount of exposure, kerma, absorbed dose or equivalent dose, or their time derivatives (rates), or related quantities of ionizing radiation (Brahme, 2014). Therefore, radiation dosimetry can be translated as the processes or methods of measuring and calculating radiation dose received by human body tissue or matter resulting from the exposure to indirect or direct ionizing radiation as well as non-ionizing radiation such as light, radio waves and ultrasound. Basically, radiation dose is classified into absorbed dose (D), equivalent dose (H), effective dose (E), internal dose, external dose, natural dose and artificial dose (Podgorsak, 2003).

Based on (Podgorsak, 2006), radiation dosimeter consists of a radiation sensitive cavity surrounding by wall, is positioned into the phantom that is equal to composition of tissue in the sort of that its reference factor (generally the centre of the cavity volume) correlate with the point A at depth z at centre beam of radiation as shown in Figure 2.1. Amount of absorbed dose at a given point A in a patient is executed with the aid of measuring the dose on the corresponding point A in a tissue-equivalent phantom.

External radiation source produce radiation beam that is characterized with the aid type of radiation and how much energy from the beam as well as by the source-surface distance (SSD) and field size A on the surface of the water phantom.

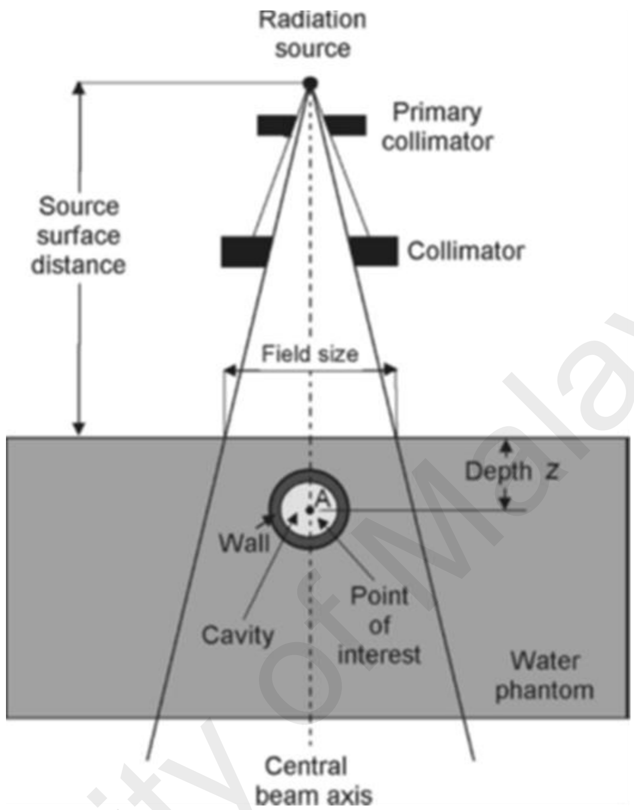


Figure 2.1: Radiation dosimeter (Podgoršak, 2006)

Assessment of internal dosimetry is depending on a selection of monitoring, bio-assay or radiation imaging techniques. While for external dosimetry is depend on the measurements with a dosimeter or contained from measurements made by other instruments for radiological protection that mainly used in medical imaging, nuclear medicine and radiotherapy where the latter is the main focus of this study (Doerfel et al., 2008). Accuracy and precision are very important aspect in radiotherapy with the main aim is to kill the cancer cells while minimize irradiation to the healthy tissues and organs and the risk of severe side effects by using dosimetry.

Medical dosimetry like radon monitoring in buildings is other significant areas where the need of measuring absorbed dose and any collateral absorbed dose must be monitored.

2.2 Characteristics of An Ideal Dosimeter

In medical dosimetry, an ideal dosimeter should exhibit the following characteristics (De Wagter, 2004):

1. High accuracy and precision
2. Wide dose detection range
3. Low detection limit
4. Linearity of signal with dose
5. Dose rate independence
6. Energy independence
7. No directional dependence
8. High spatial resolution
9. Convenient use and readout procedure

In radiotherapy dosimetry, accuracy and precision generally involve or associated or deal with the measurement of uncertainty. Reproducibility to get the same or almost the same of the measurements under similar conditions affected the precision of the dosimeter. Higher reproducibility contributes to higher precision. High precision is also involved with a small standard deviation of the distribution of measurement results.

The accuracy of dosimeter is related to the proximity of their expectation value to the 'true value' of the measured quantity. The uncertainty is a parameter that describes the dispersion of the measured values of a quantity. It is evaluated by statistical methods (type A) or by other methods (type B), has no known sign and is usually assumed to be symmetrical (Altman & Bland, 1983).

Larger range that are useable for detection represents an ideal dosimeter where it has the ability to detect radiation from a low dose to a high dose. Background radiations come from surrounding and noise created by the instrument or system contribute to that unwanted fluctuations that affected the lowest detectable radiation. The detection of lowest limit is generally determined by the fluctuations of the background readings. Wider range of detection made the detectors are useful to detect any kind or radiation that from higher energy to low energy of radiation with only using one detector.

Ideal dosimeter should give the readings that are linearly proportional to the given dose. But, after a sets of dose range or limits non-linearity usually occur. The linearity range and the non-linearity respond based on the type of dosimeter and its physical characteristics. Generally, the non-linearity respond should be corrected for due to the combined effect with its reader which might exhibit non-linearity behaviour as well.

A perfect dosimeter must have steady reaction at two distinctive dose rates. This is specifically of significance where in short times such high doses are given with the radiation created by linear accelerators (LINAC). In any case, in actuality, dose rate may impact the readings on dosimeter and the suitable adjustments are needed.

The energy response of dosimeter should be flat (no difference) over a selective spectrum of radiation qualities. Generally, dosimeter should response linearly to the radiation energy or beam quality, any difference behaviour of a dosimeter to the radiation beam quality need to be corrected for. In radiotherapy, the measurements of energy deposited to water (or to tissue) is the amount of interest that need to be known precisely. As it is extremely hard to make a dosimeter which is totally water or tissue proportional for all characteristics of radiation beam, the energy dependence is an essential characteristic of a dosimeter.

Likewise, perfect dosimeter must directional or angular independent. This characteristic is related with the variety corresponding of a dosimeter with the incidence radiation angle. However, directional dependence sometimes is particularly important on some applications in radiotherapy, such as in-vivo dosimetry. Hence, dosimeters used in radiotherapy are usually used at the same geometry as that in which they are calibrated.

A dosimeter should ideally have high spatial resolution. This feature is very important for dosimeter when used for dose measurements in small electron and photon fields as encountered in intraoperative radiotherapy (IORT), intensity-modulated radiotherapy (IMRT) and stereotactic beams. It is required in the measurement of very precise beam profile even in the penumbra region of small fields and relative dose distributions can be measured with very high spatial resolution.

Last but not least, an ideal dosimeter must be helpful to utilize and can give direct readings without any post-irradiation readout process. A dosimeter should be reusable with little or no change in its sensitivity.

2.3 Dosimeters in Radiotherapy

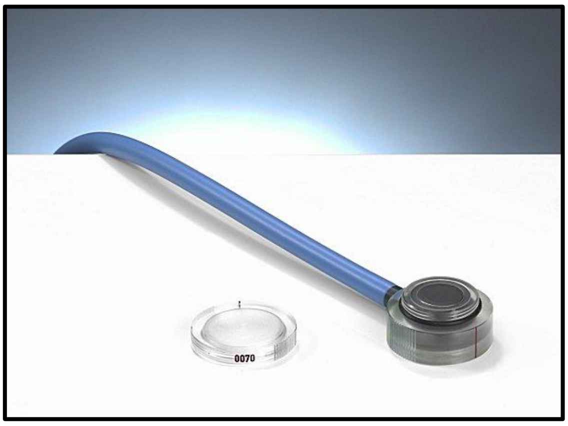
Various types of dosimeters are used in radiation dosimetry but more widely used dosimeters used in radiotherapy are ionization chamber, thermoluminescence detector (TLD), diode detector, radiochromic film and the metal-oxide semiconductor field effect transistor (MOSFET) dosimeter. The following sections describe briefly the principles of operation for the above-mentioned dosimeters.

2.3.1 Ionization Chamber

Generally, ionization chamber dosimetry systems consist of a cylindrical (thimble type) or parallel-plate (plane-parallel) chamber and an electrometer. Basically, this chamber consists conductive outer wall surrounding an air-filled cavity and a collecting electrode at the centre of the cavity. When a polarizing voltage is applied to the chamber, high quality insulator is used to separate the wall and the collecting electrode in order to reduce the leakage current. Due to measuring over a fixed time interval of the chamber current of an order of 10^{-9} ampere (A) or less or charge collected, the ionization chamber always operates with the help electrometer to get a high gain, negative feedback, operational amplifier with a standard resistor or a standard capacitor in the feedback path (Bourland, 2012).

The most common models of ionization chamber applied in radiotherapy are cylindrical ionization chamber and parallel-plate ionization chamber. The advantages of cylindrical chamber are it has smaller active volume between 0.1 cm^3 to 1 cm^3, internal diameter of not more than 7 mm and internal length of not more than 25 mm. The chamber wall is made up of material with low atomic number (Z) and is tissue or air equivalent of the thickness less than 0.1 gcm^{-2}. (http://www.ptw.de/detector retrieved 2018)

Based on the recommendation by IAEA TRS 398, the parallel-plate chamber is suitable for dosimetry of electron beams that energies below 10 MV. The steps to establish the build-up region of MeV photon beams used this chamber for measuring surface dose and depth dose. The characteristic mention above, made the ionization chamber one of the most suitable detectors used in radiotherapy nowadays primarily to measure the absorbed dose for quality assurance and 2D dose verifications. (Andreo et al., 2000)



(a) **(b)**

Figure 2.2: (a) PTW Farmer® Ionization Chambers (b) PTW Markus® Electron Chamber (http://www.ptw.de/detector retrieved 2018)

2.3.2 Thermoluminescent dosimeter (TLD)

After received an initial irradiation such as α, β, X-rays or even UV rays is given to a phosphor then is stimulated using thermal to measure the radiation absorbed by the phosphor is known as thermoluminescence (TL) dosimeter. When exposed to radiation, certain crystals would store the absorbed energy in 'traps'. This trapped energy is released as ultraviolet light when subjected to heating temperature of 200 - 300^{o}C. A measure of amount of emitted light could lead to an estimation of the previously absorbed dose (Murthy & Reddy, 2008).

Numerous materials have thermoluminescence properties. Lithium fluoride (LiF), which is nearly to tissue equivalent and calcium fluoride (CaF), which is not tissue equivalent are the two types of thermoluminescent dosimeter (TLD) that are often use as a dosimeter. Thus, lithium fluoride is the most widely recognized TLD material utilized at diagnostic X-ray energies. This has the benefits of an atomic number (Z = 8.2) nearly to that of tissue so that the sensitivity, i.e. light output per unit of absorbed dose, is not strongly dependent on the X-ray spectrum (Allisy-Roberts & Williams, 2007).

Usually, the TLD has been used to measure the entrance surface dose, in vivo patient for dose monitoring throughout the treatment and for personnel monitoring for radiation safety purposes. Prior to measure dose of entrance beam whether in 2D and 3D conformal plans TLD is placed on the patient surface. More generally to verify skin dose in anatomically critical areas for example above scars or on the contra-lateral breast, the TLD can also be applied and sometimes has also been used for intracavitary applications. But, all the applications using the TLD need a calibration factor that usually should be acquired before use as a dosimeter. (Dieterich et al., 2015)

(a) (b)

Figure 2.3: Thermoluminescence dosimeter (a) in vivo (b) personnel monitoring (Hasvold, 2008)

2.3.3 Silicon diode detector

The p-n junction diode made up the silicon diode dosimeter. To make the opposite type material, n-type or p-type silicon and counter-doping the surface are taken in order to produce the diodes. These diodes are point to as n-Si or p-Si dosimeters, determined by the base material. Including the depletion layer, the electron-hole (e-h) pairs inside the dosimeter is produced by the radiation that absorbed. Usually, for radiotherapy dosimetry the suitable diode is p-Si type, because it is less affected by radiation damage and has a much smaller dark current. (Podgorsak, 2003)

Mainly, the diodes give higher advantages in small fields for example in stereotactic radiosurgery or high dose gradient areas that involve the penumbra region. The depth dose measurements for electron beams often used the silicon diode detector. For the use in water phantoms, this detector is packaged in a waterproof encapsulation to use as beam scanning devices. Likewise, diodes are generally utilized as a part of routine in-vivo dosimetry on patients or for bladder or rectum dosage measurements (Krammer, 2011).

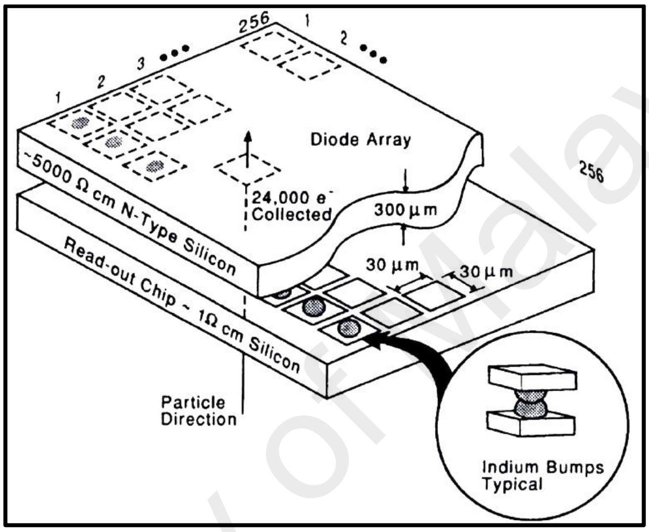


Figure 2.4: Silicon detector attached with the readout chip (Krammer, 2011)

2.3.4 Radiochromic Film

Radiochromic film consists of a single or double layer of radiation-sensitive organic microcrystal monomers, on a thin polyester base with a transparent coating. Upon irradiation, the colour of radiochromic films become to a shade of blue. Darkness of the film increases with increasing absorbed dose. No processing is required to develop or fix the image. Below is the Radiochromic Film Characteristic:

- Polymer-based (Z~7)
- Nearly Tissue Equivalent
- NOT Sensitive to Light
- Handle in Room Light
- Easy to Position Accurately

- Self-Developing
- Instant Colour Change
- Water Resistant
- Weak Energy Response (Model Dependent)

Image formation of radiochromic film can be defined as radiochromic effect. It involves the direct colouration of a material by the absorption of ionizing radiation, without requiring latent chemical, optical, or thermal development or amplification. The radiochromic process basically is the production of immediate permanent coloured images of a radiation exposure pattern in a solid, with or without ‘‘fixing’’ of the sensor medium against further change. A typical radiochromic film, protected from further irradiations, can serve as archival radiographic imaging and data-storage media (Niroomand-Rad et al., 1998).

2.4 Gafchromic HD-V2 Film

Gafchromic HD-V2 film (Ashland Inc., Kentucky United States) is one of the radiochromic film made for the quantitative measurement of high-energy photons absorbed dose. Characteristic of HD-V2 film which self-develop, made it an ideal dosimetry for the less process condition. Hence, this film no need of post exposure processing, due to no chemicals to deal off and unneeded of a darkroom to process the film (Ashland, 2012).

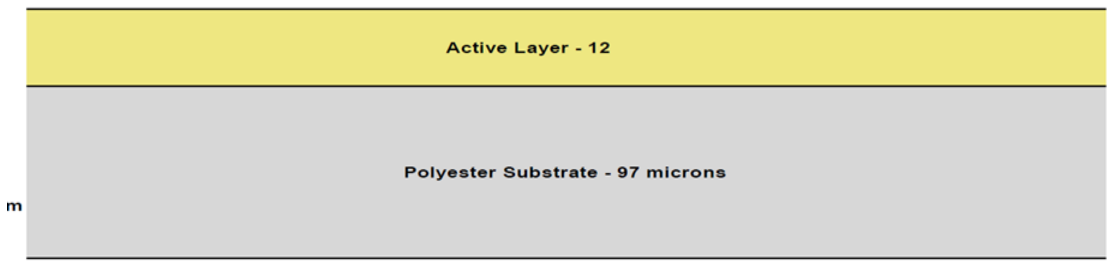


Figure 2.5: Configuration of Gafchromic HD-V2 Dosimetry Film (Ashland, 2012)

The design of Gafchromic HD-V2 film is asymmetric as presented in Figure 2.2. The component of the film consists of an active layer with thickness of 12 µm that has active component, marker dye, stabilizers and other components thus made the response of the film an energy independent. However, the active layer thickness may slightly different from batch-to-batch. A clear polyester substrate with thickness of 97 µm is coated below an active layer (Ashland, 2012). Unlike other present models HD-810, EBT3 and MD-V3, gafchromic HD-V2 is applicable to low energy (a few keV) beams since this newly film has no surface-protecting polyester layer for the active layer.

The range of HD-V2 film sensitivity is from 10 to 1000 Gy that cause it suitable for high energy beams such as SRS technique. According to the manufacture (Ashland, 2012), to get higher measurement of the film sensitivity to the expose doses is by using the red channel of a colour (RGB) scan. This because of the nature red-absorbing that has more dose-sensitive dye through the transmission (T) or the optical density (OD, $T = 10^{-OD}$) (Ashland, 2012).

Table 2.1: Specification of Gafchromic HD-V2 film (Ashland, 2012)

Property	GAFChromic® HD-V2 Film
Configuration	Active layer on 3.8 mil (97 µ) clear polyester substrate
Size	8" x 10", other sizes available upon request
Wide dose range	10 to 1000 Gy
Energy dependency	< 5 % difference in net density when exposed at 1 MeV and 18 MeV
Dose fractionation	< 5 % difference in net density for a single 100 Gy dose and five cumulative 20 Gy doses at 30 min intervals
Dose rate response	< 5 % difference in net density for 10 Gy exposures at rates of 3.4 Gy/min and 0.034 Gy/min
Stability in light	< $5x10^{-3}$ change in optical density per 1000 lux-day
Stability in dark (preexposure)	< $5x10^{-4}$ optical density change/day at 23 °C and <$2x10^{-4}$ density change/day refrigerated
Uniformity	Better than 3 % in sensitometric response from mean; dose uniformity better than ±2 % with FilmQAPro and triple channel dosimetry

Based on the properties of HD-V2 film as mentioned, we here adopt the Gafchromic HD-V2 model, which is a successor model from HD-810 so that can be used high dose dosimetry in radiotherapy. Thus, the aim of this study was to utilize the newly released Gafchromic film type HD-V2 film as one of the radiation dosimeters in stereotactic radiosurgery.

2.5 Advantages and Disadvantages of Radiochromic Film

Conventional dosimeters like ionization chamber, TLD and semiconductor, are not able to offer high spatial resolution which is advantageous for measurement and quality control at gradient areas of higher dose. Conversely, an almost tissue-equivalent radiochromic film with the characteristic of high spatial resolution could fulfil the dosimetric needs and current advancement in radiotherapy. Therefore, radiochromic film is useful for assessing high dose regions in dosimetry. For example, radiochromic film could give accurate dose distribution in the close vicinity of brachytherapy (Meigooni et al., 2005) and dose measurement for small radiation fields used in stereotactic radiosurgery (Massillon-JL et al., 2012).

Radiographic film also offers high spatial resolution but is not suitable because of its high Z material and energy dependence, particularly at low levels of radiation energy. The most common type of radiochromic film which is Gafchromic film such as EBT film, it does not show energy dependence, but the dose measured for pre-treatment plan verifications should be at least 1 Gy (Chełmiński et al., 2010). Also, radiochromic films do not need chemical processing because it is self-developing. The organic-based dye of these films changes colour due to the polymerization when exposed to radiation. Unlike readout process for radiographic film, chemical film processing is eliminated and replaced by flatbed scanner. Radiochromic film is easy to handle and is not sensitive to room light.

The characteristic of radiochromic film is independent to the dose rate, which is able to give an accurate dose measurement from ranges 1 Gy up to many kGy and this is very useful in medical radiation dosimetry. Radiochromic film does not have the saturation properties curve problems of common x-ray film (toe and shoulder regions of Hutter-Driffield curve) and hence, has a better relationship of film exposure and pixel value (Iqeilan, 2007). A flatbed scanner could be used to read and analyse and does not have the limitations of x-ray film digitizer also.

One of the drawbacks of radiochromic film is the magnitude of response variation when used for lower energy X-ray. It was found that adequately smaller of an energy response (less than 6% across the range 30 kVp to 50 kVp) to enable use of the Gafchromic XR Type-R film for dosimetric intercomparing between devices used in intraoperative source (Ebert et al., 2009). Also, radiochromic film response to radiation exposures less than 50 mGy is not noticeable due to the flatbed scanner cannot measured the small changes in film colour, thus making the utilization of this type of film in common angiography procedures difficult (Iqeilan, 2007). Nevertheless, there are few types of radiochromic films with better sensitivity in the X-ray diagnostic field, could be used for comprehensive study, like dental CT dosimetry, by adjusting the size of film samples. It was reported that effective dose values for Gafchromic XR-QA are 107 μSv and 117 μSv (vary of 8.6%) respectively for the cone beam CT and of 523 μSv and 562 μSv (vary of 7%) respectively for the multi-slice CT in dental CT dosimetry (Rampado et al., 2014).

Last but not least, a calibration curve needs to be established for every batch (with specific lot number) of film. The calibration procedure is quite time consuming and must be carried out with the use of ionization chamber in order to ensure the accuracy of the measurement of the delivered dose.

2.6 Application of Radiochromic Film in Radiotherapy

Contrasted to generally applicable detectors used in therapeutic applications the radiochromic films are almost insensitive to low radiation. Because of this make them suitable and perfect for dosimetry where high doses can be utilized based on the characteristic of less sensitivity to low radiation. A case of such a circumstance is the dosimetry in the quick region of brachytherapy sources. If the energy of radiation is too high the conventional detectors can damage which becomes an issue in brachytherapy due to the inverse square law, doses of radiation can be very high at places close to the radionuclide such as Cobalt-60.

Other crucial feature of radiochromic films is the composition of elements used inside them near to composition of water. This contributes to the reduction of their sensitivity to photon strength for applications that needed determination of dose added to water. Finally, the radiochromic films are available in the form of a two-dimensional dosimeter but the dosimeters must be calibrated before use. There are a lot of use of radiochromic films in medicine and some of the applications are mentioned below. (Niroomand-Rad et al., 1998)

2.6.1 Stereotactic radiosurgery (SRS) dosimetry

For example, irradiation of intracranial lesions used small fields of radiation beam so radiochromic film was used study the effects of electron disequilibrium (Bjarngard et al., 1990). At central axis, showed that increasingly reduce of the dose cause by electron disequilibrium for size < 1.0 cm. When the detector is too big, it directs to measurement artifacts, as was easily detected using ionization chambers.

In order to measure the amounts of doses absorbed from the radiation beams given, optimum resolution is required where radiographic and radiochromic films were used with evaluation using densitometric.

Even at small field sizes, the effect by phantom-scattered photons was important, and based on the experimental results the scatter factors were determined.

Associated to the small fields dosimetry, the same issue was rise up by (McLaughlin et al., in 1994). Gamma-ray stereotactic surgery units at Mayo Clinic and the University of Pittsburgh did some study as an indication to show the suitability of different size of field as parameter 4, 8, 14 and 18 mm to measure the dose absorbed using the calibrated radiochromic films. Conventional methods of dosimetry and computational dose planning system were used to compare with radiochromic films. The result show with indicated agreement to within only ± 2%. Based on the study, (McLaughlin et al., 1994) had drawn some conclusions. High spatial resolution information of dose, dose profiles, and isodose curves can be acquired using radiochromic film such measuring and calculating the tolerance value for testing and dose of quality control.

2.6.2 In Vivo Dosimetry

American Association of Physicists (AAPM) and the European Society of Therapeutic Radiology and Oncology have recommended that patient dose verification, in vivo dosimetry (IVD) is a crucial part of a quality assurance (QA) programme in radiotherapy in order to enhance the quality of treatment and patient care (Vasile et al., 2012). In vivo dosimetry (IVD) is an essential part in external beam radiotherapy (EBRT) to identify treatment planning errors, to evaluate clinically relevant variation between prescribed and delivered dose, to measure dose received by individual patients, and to achieve valid tolerance level (Mijnheer et al., 2013). It is because computer simulation of radiation dose is not absolutely accurate, and particularly for correction-based algorithms.

Even modern treatment planning software with superposition/convolution techniques may have errors, particularly at the accuracy of tissue inhomogeneity corrections (Papanikolaou et al., 2004).

Therefore, in vivo dosimetry gives an additional check to make sure that systematic errors have not been obtained during the treatment planning process. If an error is detected, treatment plans should be re-evaluated and corrections are done before the delivery of radiation which could cause irreversible problems.

Radiochromic film could be a suitable dosimeter for in vivo dosimetry due to its high spatial resolution in dose measurement, weak energy dependence and tissue equivalent material. The feasibility of in vivo dosimetry with radiochromic film has been demonstrated by several studies. It is found that Gafchromic EBT film are an ideal alternative to thermoluminescent dosimeters (TLDs) in in vivo dosimetry for total body irradiation (TBI) but give a challenging task due to the comprise of source-to-surface distance (SSD), low dose rates, and the usage of beam spoilers. Doses measured by EBT film were compared to conventional dosimeter measurements that used thermoluminescent dosimeters (TLDs), giving an agreement of 4.1% and 6.7% for the phantom and patient measurements respectively (Su et al., 2008).

2.6.3 General Quality Assurance

Radiochromic film also acts as a quality assurance tool in radiotherapy. It can be used to perform some quality control tests which could not be accomplished using other dosimeters. Radiochromic films such as EBT film and Radiotherapy Quality Assurance (RTQA) film offer a quick and simple method for medical physicist to conduct the tests in order to check radiation and light field coincidence, beam symmetry and flatness, star pattern and picket Fence analysis for multi-leaf collimator (MLC) QA. Also, the RTQA films cut into strips are suitable for source dwell position check in brachytherapy.

2.6.4 Patient Specific Quality Assurance

In general, quality assurance (QA) in radiotherapy can be examined under two topics, machine QA and patient specific QA. Machine QA actually is general quality assurance in radiotherapy routinely performed by physicist and could directly affect the results of patient specific QA within tolerance limit. The purpose of patient specific quality assurance (QA) is to ensure the quality of the delivered radiation treatment matches to what is planned, in terms of tumour coverage and normal tissue sparing. It can be done using various types of dosimeters but radiochromic film will be focused because it is the main dosimeter to be investigated in this study. Radiochromic film can be used in pre-treatment QA for various types of treatment techniques such as intensity modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), and tomotherapy which require high accuracy in dose delivery to individual patients. It can be used as a planar 2D detector with suitable phantom and as similar to other 2D detectors, gamma analysis of dose difference and distance-to-agreement is possible. (Haydaroglu & Ozyigit, 2013).

CHAPTER 3: METHODOLOGY

3.1 Introduction

The Gafchromic HD-V2 film, which is the latest type of Gafchromic film, is introduced to replace the previous generation of film for high dose measurement, the Gafchromic HD810. Ensuring the accuracy of dose measurement is a fundamental and indispensable step in order to characterise any version of film. The first part of the study established a calibration curve and mathematical equation for dose response of the Gafchromic HD-V2 film. This was followed by investigation of a number of basic physical characteristics of the film which include the energy dependence, dose rate dependence, angular dependence and dependence on post-irradiation with time. The effect of scanning orientations on the film dose response was also assessed. The second part of the study involved the use of Gafchromic HD-V2 film for dose verification of real clinical treatment plans for stereotactic radiosurgery (SRS). The following sections describe the methodologies used in this project.

3.2 Film Calibration

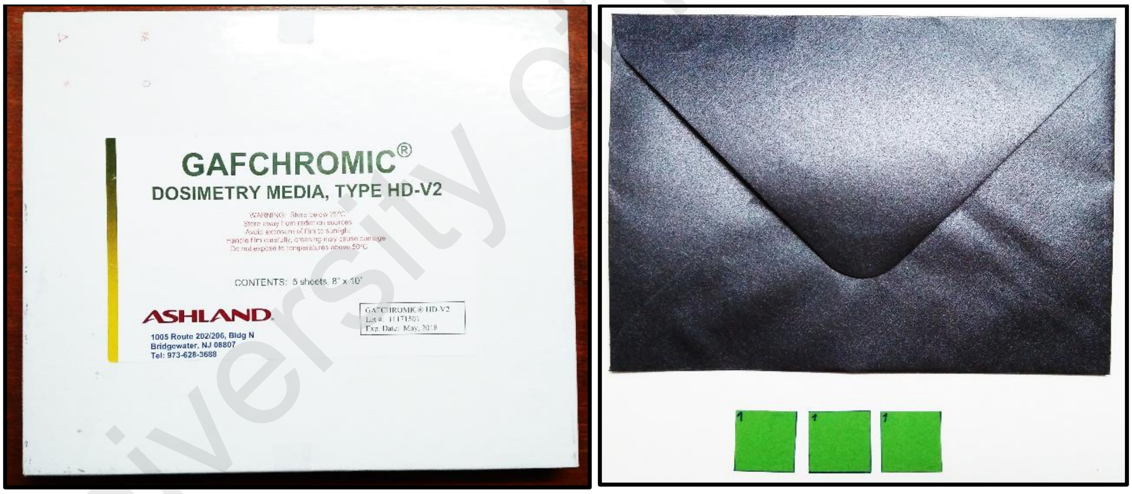
The most important procedure for any film dosimetry is the film calibration to establish a film calibration curve for determination of dose. A calibration curve correlates the irradiation dose to the pixel values in the scanned films.

Film calibration process consists of the following procedures:

1. Film preparation
2. Film irradiation
3. Film scanning
4. Film analysis

3.2.1 Film Preparation

Gafchromic HD-V2 film (Lot#.: 11171501, Expiry date of May 2018) in its container box as shown in Figure 3.1 (a) was cut into pieces of 2 cm × 2 cm prior to exposure and marked to ensure retention of scanner orientation (Butson et al., 2006) as shown in Figure 3.1 (b). This step was repeated for all the characterization tests and dosimetric verification measurements. For each sheet of Gafchromic HD-V2 film used for calibration or experiment measurements, three pieces of film were left unexposed for background determination. The films were handled by following the procedures described in the AAPM Radiation Therapy Committee Task Group 55 report (Niroomand-Rad et al., 1998). Furthermore, in order to minimize the films exposed to light, all films were kept in black envelopes when they were not in use.



(a) (b)

Figure 3.1: (a) The box of Gafchromic HD-V2 film that used in this study. (b) Three pieces of HD-V2 films with the size of 2 cm x 2 cm were labelled with number at the corners of the film to ensure the film orientation. The black envelope used to keep the films from visible and UV light.

3.2.2 Film Irradiation

Films were irradiated with either 6 MV or 10 MV photon beam, which was generated by a Novalis Tx linear accelerator (Varian Medical Systems, Palo Alto, CA) at the Clinical Oncology Unit, University Malaya Medical Centre (UMMC) as shown in Figure 3.2.

Figure 3.2: Linear accelerator (Novalis Tx) at Oncology Unit of University Malaya Medical Centre (UMMC).

Twenty-one pieces of Gafchromic HD-V2 film were separated into seven groups and each group was irradiated to a dose from 10 to 25 Gy (10, 12, 14, 16, 20, 23 and 25 Gy respectively). The film irradiation was set-up in which the films were placed at the depth of maximum dose of 6 MV photon beam with 1.5 cm of solid water phantom as build-up on the top of film as shown in Figure 3.3. Source to surface distance (SSD) was set up to 100 cm and a field size of 10 cm × 10 cm were used. In order to prevent backscatter from the treatment couch, 20 cm of solid water phantom was placed under the films.

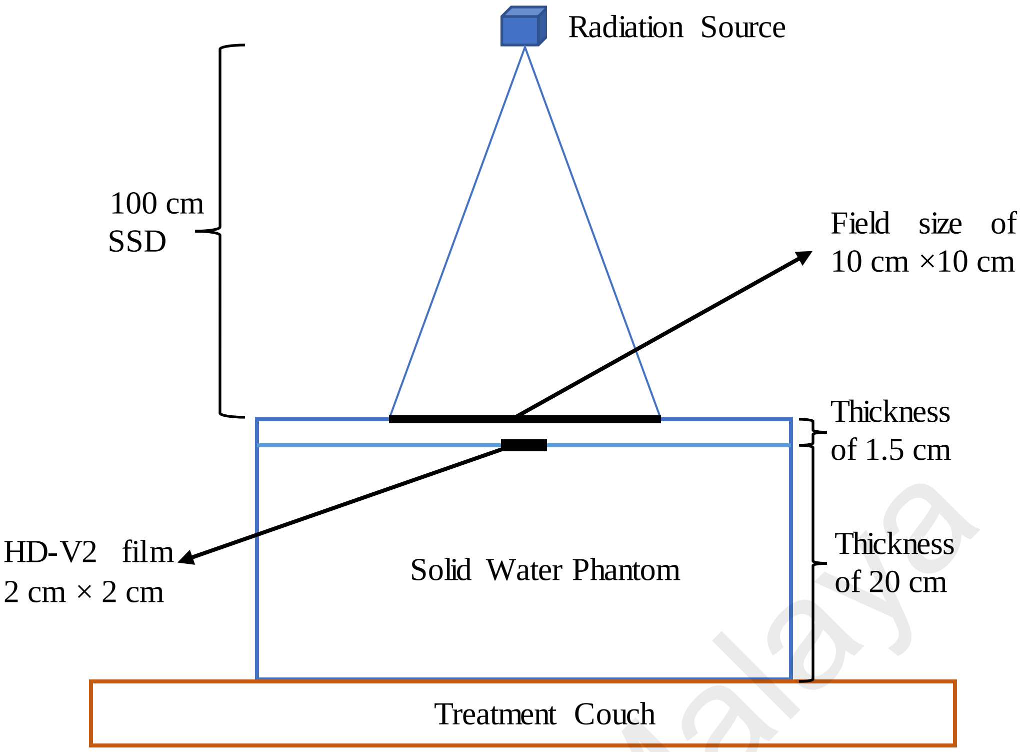


Figure 3.3: Film calibration and characterization set-up.

3.2.3 Film Scanning

All HD-V2 films were scanned at least 24 hours after irradiation to enhance the accuracy of the film analysis by allowing maximum post-irradiation colouration (Cheung et al., 2005). The film scanning orientation was maintained throughout the scanning process in order to minimize the effects of the lateral dependence artefacts (Butson et al., 2006). In addition, a cardboard template as shown in Figure 3.4 was prepared and fitted to the flatbed scanner in order to position films at a reproducible position for scanning.

Epson Expression 10000XL (Seiko Epson Corporation, Nagano Japan) flatbed scanner as shown in Figure 3.5 was used to scan all the films throughout the study. It is equipped with two scanning modes, which are the reflective and transmission mode in which the latter was used for film scanning in this study. All films were scanned using bit depth of 48-bit colour and scanning resolution of 96 dpi.

Figure 3.4: A cardboard template made of black paper was to provide a reproducible position to place the film on flatbed scanner

Before starting film scanning, the flatbed scanner was warmed up. The flatbed scanner was turned on half an hour before the scanning and five previews scanning were done. Based on (Mayers, 2011), the time for the scanner lamp to warm up would affect the pixel values of the initial scans. Based on (Devic et al., 2005), in order to remove scanner noise, multiple scans were performed to take the average values of the scanned images.

Figure 3.5: Epson Expression 10000XL flatbed scanner

3.2.4 Film Analysis

Based on the (Paelinck et al., 2007), because of data lossless property, all the scanned images were saved as tagged image file format (.tiff files). An imaging software, known as Image-J 1.51w (National Institute of Health, Maryland USA) was used in this study to performed film analysis. Image-J is a freely downloadable image analysis software package developed at the National Institute of Health (NIH) to assist clinical and scientific image analyses (Shanthi & Singh, 2011). Figure 3.6 shows a screenshot of the software when obtaining the mean pixel value with its standard deviation for red channel with a region of interest (ROI) measuring 0.58 cm × 0.56 cm at the centre on the film image.

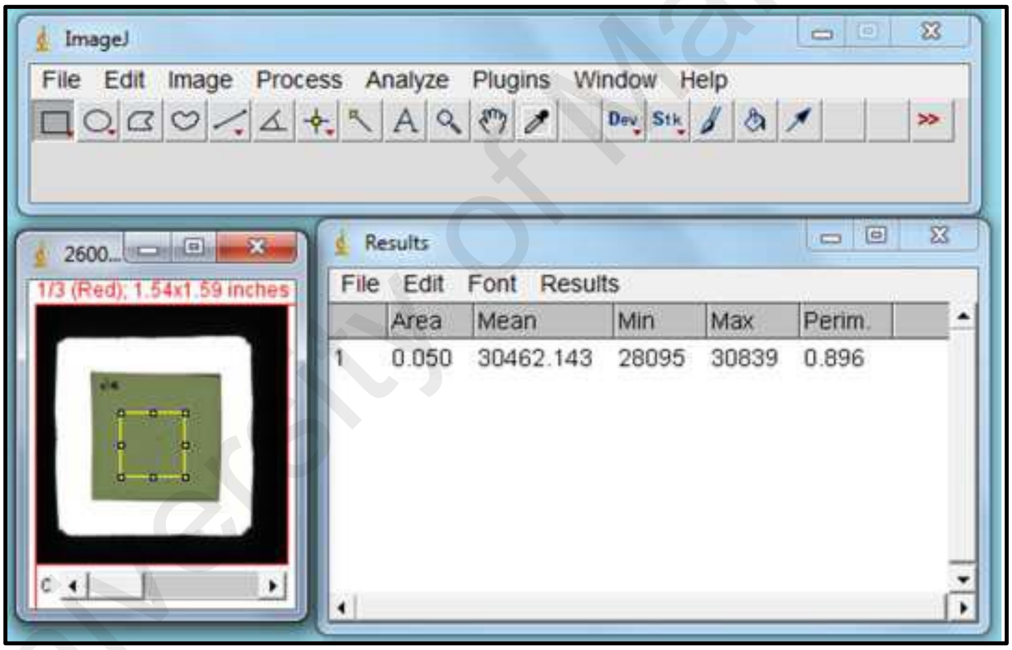


Figure 3.6: Screenshot of film analysis (measuring mean pixel value) using Image-J.

3.3 Characterization tests of Gafchromic HD-V2 film

Figure 3.7 demonstrates that three pieces of Gafchromic HD-V2 films of 2 cm x 2 cm positioned on solid water phantom close to the centre of radiation field for every test. Novalis Tx linear accelerator by Varian at the Oncology unit of UMMC was used for film irradiation.

In accordance with the rules of procedure to fulfil the statistical requirement and to minimize the random process effect during irradiation, three pieces of films were used in each measurement.

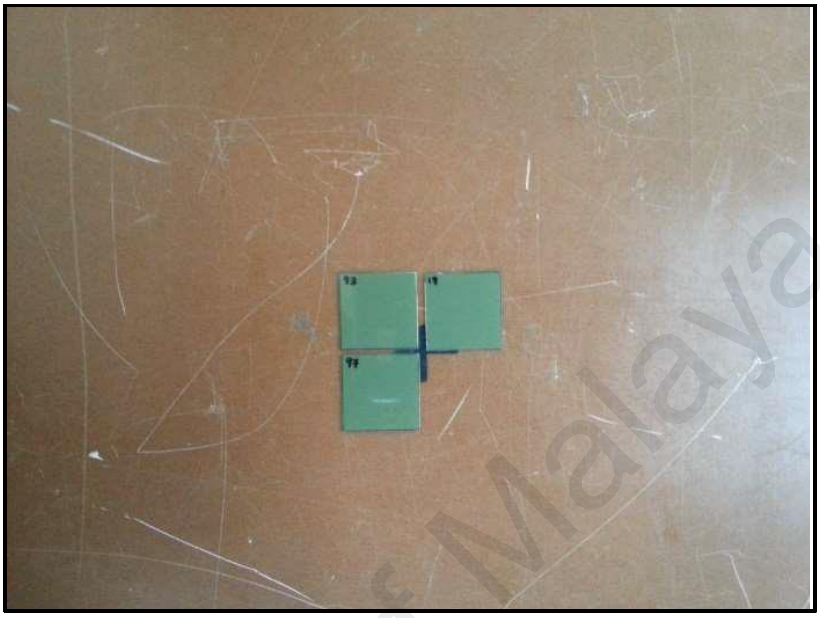


Figure 3.7: Three pieces of HD-V2 films were placed at centre of the field for irradiation.

3.3.1 Energy Dependence

The test of energy dependence was performed to investigate the consistency of HD-V2 film response over distinct photon energies of 6 and 10 MV. Seven groups of film pieces were irradiated with a dose rate of 600 MU/ min to a dose from 10 to 25 Gy (10, 12, 14, 16, 20, 23 and 25 Gy respectively).

The HD-V2 films were irradiated perpendicular to the beam at a depth of maximum dose, d_{max} of solid water phantoms act as medium. The d_{max} of 6 and 10 MV photon energy is 1.5 and 2.5 cm respectively. The field size was set to 10 cm x 10 cm, a SSD of 100 cm, and 0° collimator and gantry angle.

3.3.2 Dose Rate Dependence

Dose rate dependence test was performed to investigate the consistency of HD-V2 film performance over distinct dose rates for photon energies of 6 MV. Seven groups of film pieces were irradiated at different dose rate, where the selected dose rates were 100, 200, 300, 400, 500, 600 and 1000 MU/ min. All the films pieces were irradiated perpendicular to the beam at d_{max} of solid water phantoms with a field size of 10 cm x 10 cm, a SSD of 100 cm, 0° collimator and gantry angle.

3.3.3 Scanning Orientation

Scanning orientation test was performed to analyse the effect of HD-V2 film scanning orientation on scanner output. Five groups of film pieces were irradiated with different rate 300, 400, 500, 600 and 1000 MU/min to a dose 10 Gy. All the films pieces were irradiated perpendicular to the beam at d_{max} of solid water phantoms at 6 MV photon energy and 1.5 cm depth with a field size of 10 cm x 10 cm, a SSD of 100 cm, 0° collimator and gantry angle. The films were then scanned with different orientations such as portrait and landscape orientation and face-down (flipped 180°) orientation using flatbed scanner.

3.3.4 Angular Dependence

Angular dependence test was performed to investigate the dependency of HD-V2 film response on beam incident angle. A piece of film was sandwiched between a custom made angular dependence measurement-jig. Figure 3.8 shows the jig which is made up of two halves of a 1.2 cm-diameter and 18 cm-length Perspex cylindrical rod. The cylindrical rod was then inserted in between two pieces of phantoms. At one end of the cylindrical rod, it was rotated to particular angle with the assist of angle circle paper as shown in Figure 3.9.

The irradiation of films used 6 MV photon beam with a dose rate of 1000 MU/min. The film was placed at 1.5 cm below the phantom surface with a SSD of 100 cm, field size 10 cm × 10 cm. Five groups of films were used in this test with angles at 0°, 45°, 90°, 135° and 180°.

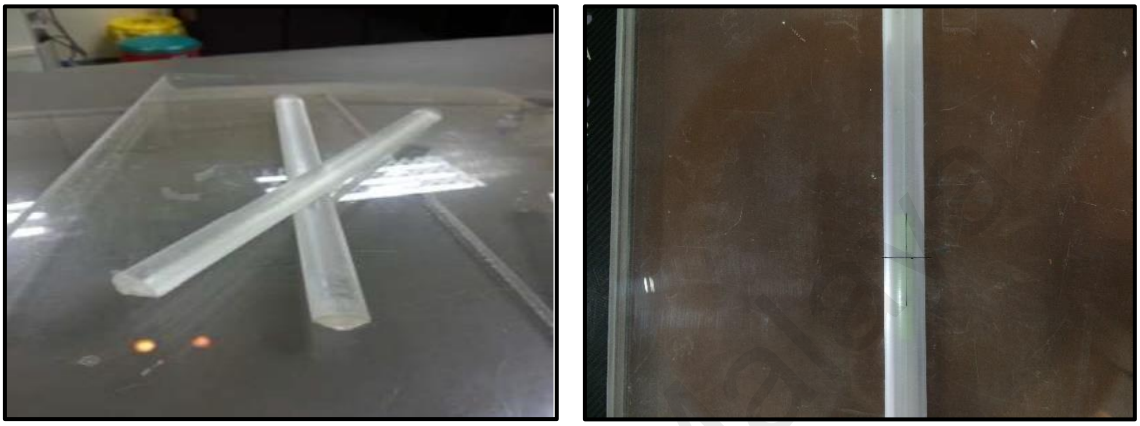


Figure 3.8: A custom made angular dependence measurement cylindrical rod.

(a) (b)

Figure 3.9: (a) The irradiation set up for angular dependence test. (b) The cylindrical rod was rotated to desired angle with the help of the angle circle paper. The angle is 0° and 90° when the film is parallel or perpendicular to the beam respectively.

3.4 Dosimetry Verification in Stereotactic Radiosurgery Using HD-V2 Film

One of the primary parts of quality assurance (QA) is dosimetric verification which is a programme created to determine and evaluate the accuracy of radiotherapy unit radiation delivery as per tolerance limits.

Based on (Krishna Murthy, 2012) it is very importance to verify dose, to ensure that adequate level quality of treatment is delivered to patients. This can be done by comparing the treatment planning system (TPS) dose distribution with equivalent distribution or point doses to film using different analysing software. The aim of this part of study is to elucidate the feasibility of HD-V2 film in the dosimetric verification for stereotactic radiosurgery (SRS) delivery.

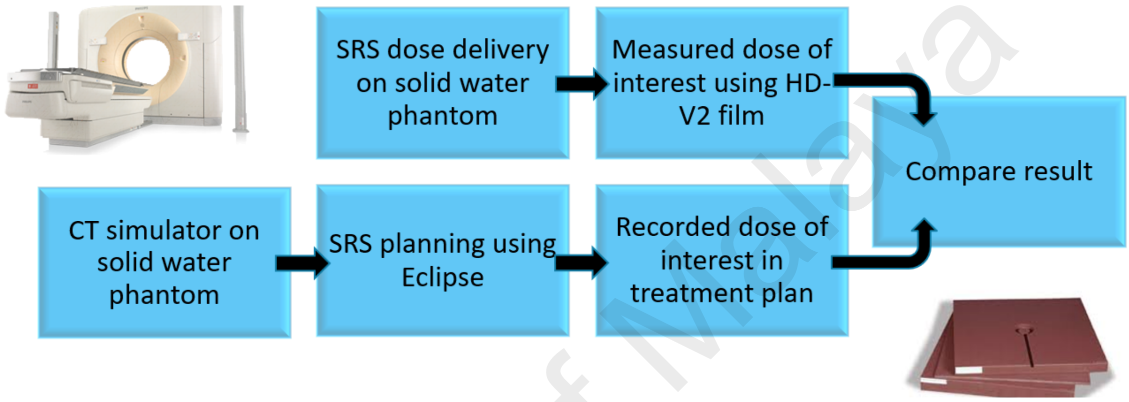
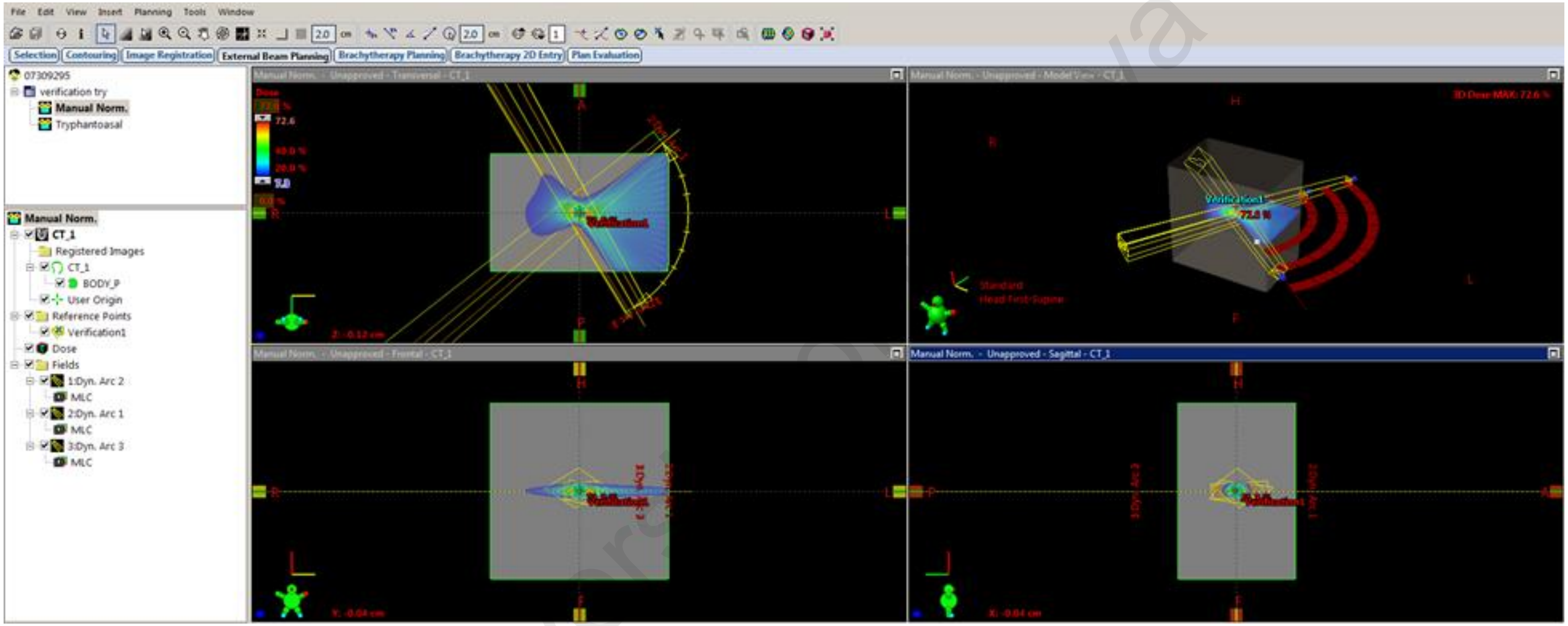


Figure 3.10: Steps of dosimetry verification in stereotactic radiosurgery using HD-V2 film

SRS treatment plans were created using Varian Eclipse version 13.6 with AAA dose calculation algorithm. Dose verification of clinical SRS radiotherapy treatment were performed with solid water phantoms. The irradiations of dose verification using Dynamic Conformal Arcs was performed using Novalis Tx linear accelerator (Varian Medical Systems, Palo Alto, CA). All radiation fields were set to co-planar. Dose at the isocentre (centre of the phantom) was determined in Eclipse TPS and measured with Gafchromic HD-V2 film in the phantom. The irradiations were carried based on the planning set up of clinically SRS case. The dose measurements by the Gafchromic HD-V2 film were compared with the TPS predicted dose.

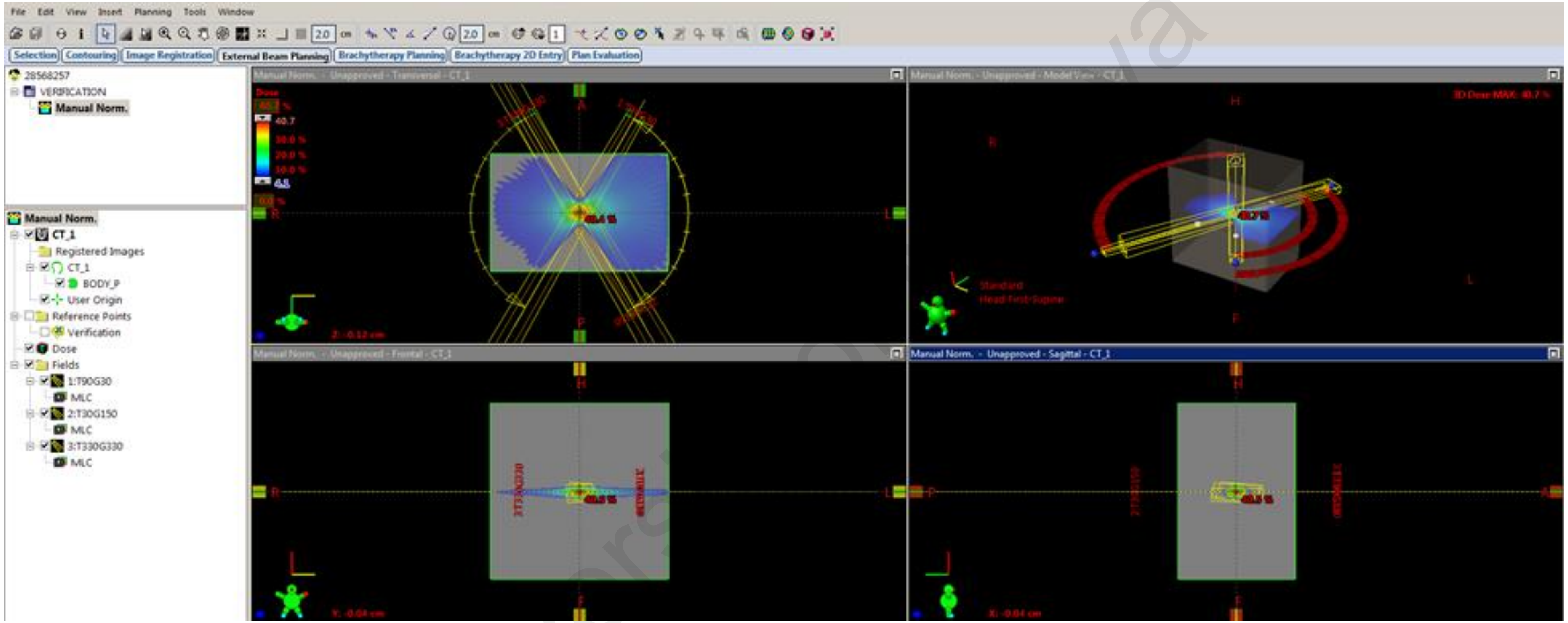
For the first clinical case Figure 3.11, 15 Gy dose was prescribed at 95% PTV isodose. By using 6 MV photon beam, the irradiations were delivered using 3 arcs with gantry angle of 150° to 50°, 50° to 150° and 150° to 50° respectively using Dynamic Arc.

For the second clinical case Figure 3.12, by using 95% of PTV isodose based prescription, 9 Gy was prescribed. The irradiations were made using parameters of 6 MV photon beam energy, 3 arcs with angle of 30° to 150°, 150° to 30° and 330° to 210° respectively gantry angle respectively using Dynamic Arc.



Group	Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	Calculated SSD [cm]	MU	Ref. D [Gy]
☑	1:Dyn. Arc 2	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.220	Varian IEC	150.0 CCW 50.0	285.0	0.0	None	3.3	+1.5	+1.8	4.5	+2.6	+1.9	-0.04	-0.04	-0.13	88.6	996	
☑	2:Dyn. Arc 1	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.250	Varian IEC	50.0 CW 150.0	45.0	0.0	None	4.9	+2.2	+2.7	4.5	+1.6	+2.9	-0.04	-0.04	-0.13	84.4	1064	
☑	3:Dyn. Arc 3	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.234	Varian IEC	150.0 CCW 50.0	85.0	0.0	None	2.6	+1.1	+1.5	4.7	+2.1	+2.6	-0.04	-0.04	-0.13	88.6	1074	

Figure 3.11: Screenshot of TPS showing dose distributions on water phantom for first clinical case set up



Fields | Dose Prescription | Field Alignments | Plan Objectives | Optimization Objectives | Dose Statistics | Calculation Models | Plan Sum

Group	Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	Calculated SSD [cm]	MU	Ref. D [Gy]
☑	1:T90G30	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.131	Varian IEC	30.0 CW 150.0	275.0	0.0	None	3.0	+1.3	+1.7	3.8	+1.9	+1.9	-0.04	-0.04	-0.13	88.4	545	
☑	2:T30G150	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.133	Varian IEC	150.0 CCW 30.0	280.0	0.0	None	2.9	+1.4	+1.5	3.5	+1.9	+1.6	-0.04	-0.04	-0.13	88.6	555	
☑	3:T330G330	ARC-I	NovalisTX 5908 - 6X-SRS	Arc Dynamic	0.138	Varian IEC	330.0 CCW 210.0	0.0	0.0	None	4.3	+2.0	+2.3	1.5	+0.9	+0.6	-0.04	-0.04	-0.13	88.4	635	

Figure 3.12: Screenshot of TPS showing dose distributions on water phantom for second clinical case set up

CHAPTER 4: RESULT AND DISCUSSION

4.1 Calibration curve

Calibration curve for Gafchromic HD-V2 film was established over a wide range of known doses from 0 to 100 Gy. The reason to establish this range of doses is because it covers the range of prescribed doses used in Stereotactic Radiosurgery (SRS) treatment.

Based on the mean pixel values (PV) measured using the Image-J software, the net optical density (OD) was calculated using the Equation 4.1 (a) below.

$$\mathrm{OD} = \mathrm{Log}_{10} \frac{mean\ PV\ unexposed}{mean\ PV\ after} \qquad \text{[Equation 4.1 (a)]}$$

Where, mean PV unexposed = mean PV without exposure

mean PV after = mean PV after exposure

Table 4.1: Calculated net OD and the uncertainties for calibrated HD-V2 films.

Dose (Gy)	Mean PV	Net OD	STDEV	COV (%)
10	41028	0.0433	0.0021	4.8
20	37575	0.0804	0.0013	1.6
30	35247	0.1082	0.0034	3.1
40	33082	0.1357	0.0027	1.9
60	29666	0.1830	0.0025	1.4
80	27133	0.2218	0.0034	1.5
100	24861	0.2598	0.0021	0.8

Table 4.1 shows the measured mean PV, calculated net OD and coefficient of variation (COV) respectively. The COV values are within acceptable range which is 0.8% to 4.8%. The relationship between COV and the standard deviation is linear such that the lower the COV, the lower the standard deviation. This will also impact to a higher precision in the net OD. Based on the table above, Gafchromic HD-V2 film has high repeatability or reliability because the variations in measurements at all range of dose are below 5%. From Table 4.1, the dose was plotted as a response function of net optical density as shown Figure 4.1.

The Epson (Expression 10000XL) flatbed document scanner (model) was used to scan the films using the red and green channels. According to the manufacturer (Ashland, 2012) and (Devic et al., 2016), the optical dose-dependent absorption for blue light almost showed flat responses over a wide range of dose. Since this dye has a strong absorption band in the blue part of the spectrum, the signal from this colour channel always uses for non-uniformity correction. Based on this reason, only the red and green channels were tested for scanning. Based on results in Figure 4.1, the red channel has a higher sensitivity with greater changes in the net optical density (OD) as a function of dose over the range from 0 – 100 Gy compared to the green channel. For a maximum dose of 100 Gy applied in this experiment, the net OD were 0.26 and 0.12 generated using the red and green channel respectively. This indicates red channel produces a wider response in the OD and hence, a greater dynamic range for the range of dose used in this experiment compared to the green channel. This concurs with the manufacturer's recommendation that the optical dose-dependent absorption is the strongest in the red light followed by green light. Thus, all subsequent measurements used the red channel for scanning.

The calibration curve was fitted using a third-degree polynomial function with the R-squared (R^2) value for green channel and red channel are 0.9999 and 0.9996 respectively. Most of the researchers such as (Butson et al., 2009, Ebert et al., 2009, Aland et al., 2011, Brown et al., 2012) applied a third order polynomial function to fit the calibration curve for radiochromic film in order to describe the relationship between the absorbed dose and net OD response. The choice of order of polynomial function for curve fitting is based on the following criteria (i) the fit function has to be consistently increasing; (ii) the fit function has to go through zero (since for zero dose the response must be zero as well) and (iii) the function gives the minimum relative uncertainty for the fitting parameters.

From the study (Moretti et al., 2009) had reported that there are some researchers have incorporated to fourth degree polynomial function for curve fitting of radiochromic film calibration.

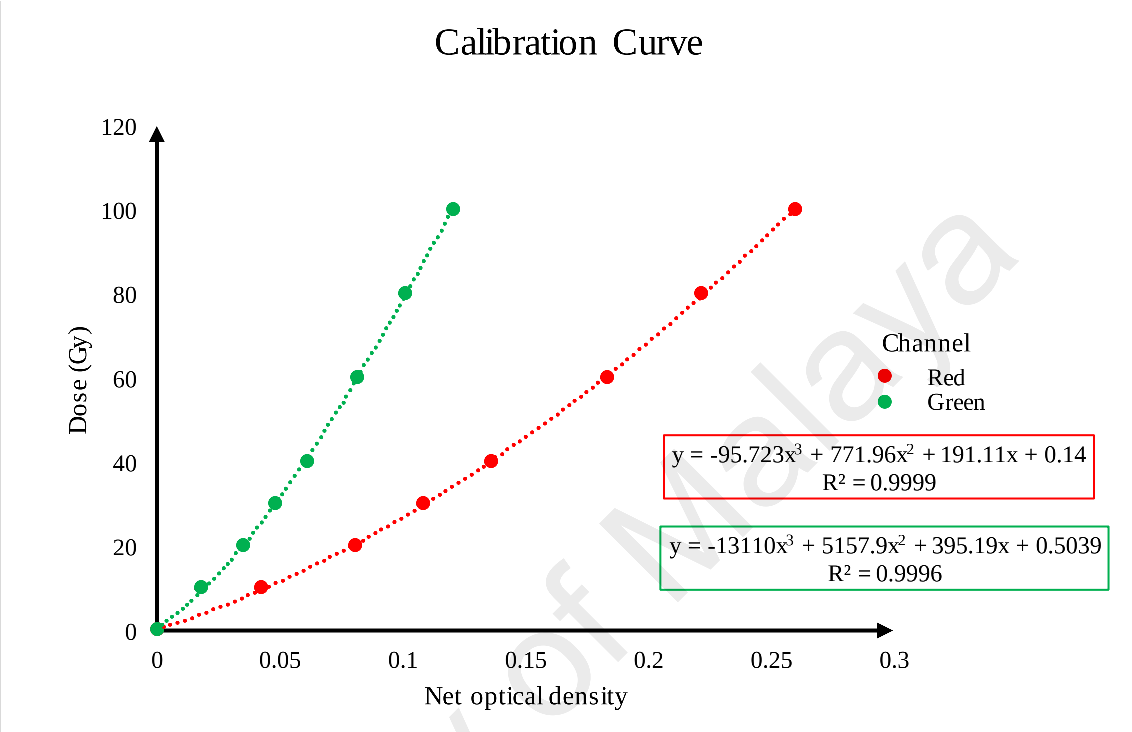


Figure 4.1: HD-V2 film calibration curve generated using the red and green channels.

The relationship between dose and net OD response for HD-V2 film in this study was described by the Equation 4.1 (b).

$$y = -95.723x^3 + 771.96x^2 + 191.11x + 0.14 \qquad \text{[Equation 4.1 (b)]}$$

Where, y = dose (Gy)

x = calculated net OD

However, to represent the net OD is 0 when dose is 0 Gy, the number of 0.14 in the Equation 4.1 (b) is not accounted for dose calculation based on the most suitable calibration function criteria.

The applicability of Equation 4.1 (b) for converting the net OD into dose was tested by comparison with known doses applied during irradiation. Table 4.2 shows the calculated dose using Equation 4.1 (b) for the dose range of 10 to 100 Gy. It was found that the maximum percentage difference between the known and calculated dose is 2.85% at a known dose of 10 Gy. The results show that Equation 4.1 (b) can be used to convert the net OD into dose, with expected maximum deviation from the true value by approximately 3%.

Table 4.2: Comparison between the known and calculated doses.

Dose (Gy)	net OD	Calculated dose (Gy)	Percentage difference (%)
10	0.0433	9.715	2.85
20	0.0804	20.306	1.53
30	0.1082	29.594	1.35
40	0.1357	39.910	0.23
60	0.1830	60.239	0.40
80	0.2218	79.320	0.85
100	0.2598	100.076	0.08

4.2 Energy Dependence

Figure 4.2 shows the net OD for HD-V2 films as a response function of the known dose rates for 6 and 10 MV photon energies. The points represent the experimental net OD data. As it can be noted, there are only small differences observed between net OD between 6 and 10 MV photon energies at a known dose rates over same doses of 10, 12, 14, 16, 20, 23 and 25 Gy.

Equation 4.2 was used to quantify the difference between net OD for both energies.

$$\% \text{ change in net OD} = \frac{net\ OD\ (6\ MV) - net\ OD\ (10\ MV)}{net\ OD\ (6\ MV)} \times 100\ \% \qquad \text{[Equation 4.2]}$$

Where, net OD (6 MV) = net OD at a known dose for 6 MV photon beam

net OD (10 MV) = net OD at a known dose for 10 MV photon beam

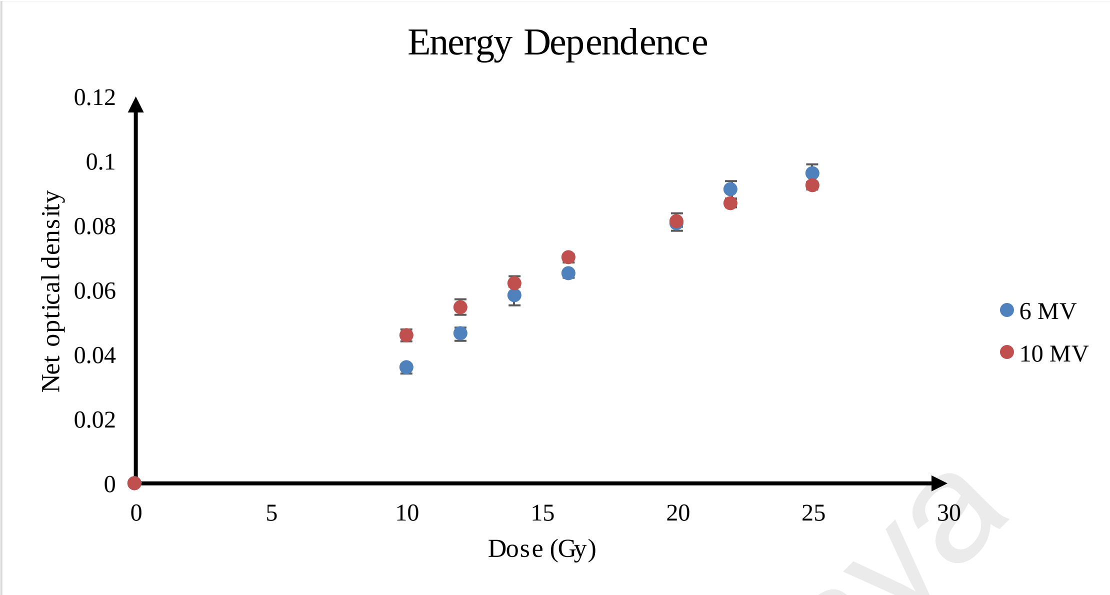


Figure 4.2: Comparison of film responses over 6 and 10 MV photon energies. Error bar which is too small to be observed, representing 1 SD for the mean reading of 3 films for each photon energy

It was noted that the net OD of both 6 and 10 MV photon energies is not significantly different from each other with deviations ranging from 0.65% to 9.5%. The maximum deviation of net OD between 6 and 10 MV energies is observed to be at 10 Gy, with a deviation of 9.5%. All the measurements were within measurement uncertainty. It can be concluded that HD-V2 film has very low energy dependency for high photon energies.

In general, the net OD of 10 MV is noted to be slightly higher to that of 6 MV. According to the (Massillon-JL et al., 2012), this variation is due to the capability of higher energy ionizing radiation to produce more colouration of radiochromic film. The results obtained in this part of study has shown that HD-V2 film has similar energy dependence characteristics with the EBT3 films, with a very low energy dependency over a wide range of dose used for radiotherapy (Chełmiński et al., 2010, Arjomandy et al., 2010). The Gafchromic HD-V2 is a low-density film as it is constructed from low atomic number materials and thus, causing it to have very low energy dependency. This is in contrast with silver halide-radiographic film which is constructed from high density materials which causes it to have high energy dependency.

4.3 Dose Rate Dependence

Figure 4.3 shows the dose rate dependence of Gafchromic HD-V2 film irradiated using 6 MV photon energy. Each point on the graphs represents the average value of net OD of three films irradiated with the same dose rate at a known dose. There is no significant difference observed as shown in Figure 4.3.

The deviation of dose rate was quantified using the Equation 4.3 below by taking dose rate of 1000 MU/min as control group.

$$\% \text{ change in net OD} = \frac{net\ OD\left(1000\ \frac{MU}{\min}\right) - net\ OD\left(x\ \frac{MU}{\min}\right)}{net\ OD\ (1000\ \frac{MU}{\min})} \times 100\ \% \qquad \text{[Equation 4.3]}$$

Where, net OD $_{(600\ MU/min)}$ = net OD at a known dose for 600 MU/ min

net OD $_{(x\ MU/min)}$ = net OD at a known dose for a chosen dose rate

The average deviation of net OD for all dose rates is less than 4.94%. Error bars were too small to be observed from the graphs, representing 1 SD for the mean reading of 3 films. The average of 1 SD for each dose rate is within the range of 0.05% to 0.09%.

Theoretically, the dose delivered to the film as well the patient will not be altered by the changing of the dose rate radiation delivery. Dose rates will instead have impact on the duration of radiation delivery time. According to (Mayers, 2011), the phase of radiofrequency (RF) would be altered and gun pulses are released from electron gun remained at constant rate cause the change of the dose rate. When the gun pulse and wave are coincident, a pulse of radiation beam will be produced and delivered.

Based on the result of the average deviation that less than 4.94% and R^2 that is nearly equal to 0, we can conclude that HD-V2 film is dose rate independent which has fulfilled one of the ideal radiation detector criteria. This concurs with the dose rate independent characteristics of the EBT3 film.

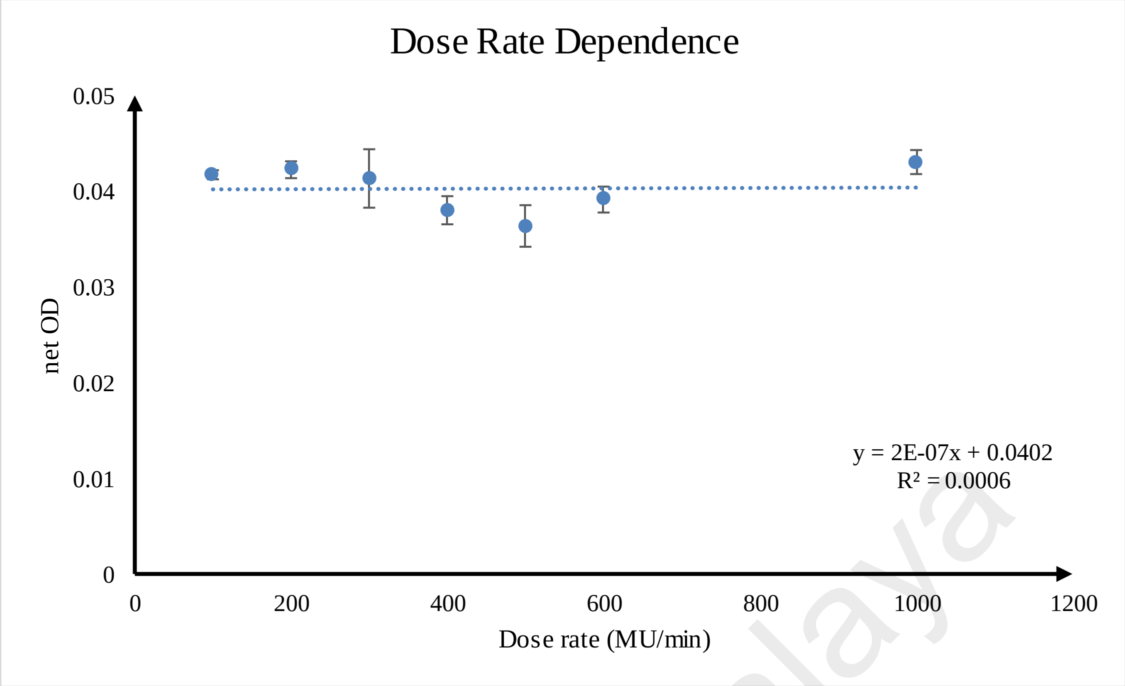


Figure 4.3: The dose rate dependence of HD-V2 film for 6 MV photon energy.

4.4 Scanning Orientation

Scanning orientation test was done to analyse the effect of HD-V2 film scanning orientation on scanner output. The graphs were plotted in a same way as previous test. It could be seen that there is no significant difference for portrait and landscape orientations graphs in Figure 4.4.

The deviation of film scanning orientations was quantified using the Equation 4.4 below by using the scanning position in the portrait orientation as control group.

$$\%\ \text{change in net OD} = \frac{net\ OD(potrait) - net\ OD(landscape)}{net\ OD\ (potrait)} \times 100\ \% \qquad \text{[Equation 4.4]}$$

Where, net $OD_{(portrait)}$ = net OD obtained from film scanned at portrait orientation

net $OD_{(landscape)}$ = net OD obtained from film scanned at landscape orientation

Net $OD_{(portrait)}$ and net $OD_{(landscape)}$ was then replaced by net $OD_{(face\text{-}up)}$ and net $OD_{(face\text{-}down)}$ respectively for calculating the percentage change between face-up and face-down orientations.

The deviation of net OD at all dose rates for 6 MV photon energy is within the range of 0.15% to 2.7%. Error bars were too small to be observed from the graphs, representing 1 SD for the mean reading of 3 films. The result shows that there is no significant difference in the net OD when scanning HD-V2 films either in the portrait or landscape orientation. This property is desirable as the film can be positioned in any orientation (with regards to portrait and landscape orientation) during irradiation and scanning.

Based on (Bartzsch et al., 2015), the predecessor of Gafchromic HD-V2 film, the Gafchromic HD-810 film, have polarizing properties rendering the readout sensitive to the film orientation because of its crystal structure. However, the result on the scanning orientation for HD-V2 is in contrast with other Gafchromic films, where scanning orientation will significantly affect the OD produced. Based on (Aland et al., 2011), the polarization of the scanning light with the alignment polymer molecules in the film's active layer give the variety to the results. These films therefore need to be marked before irradiation, in order to get an accurate result by minimize uncertainty.

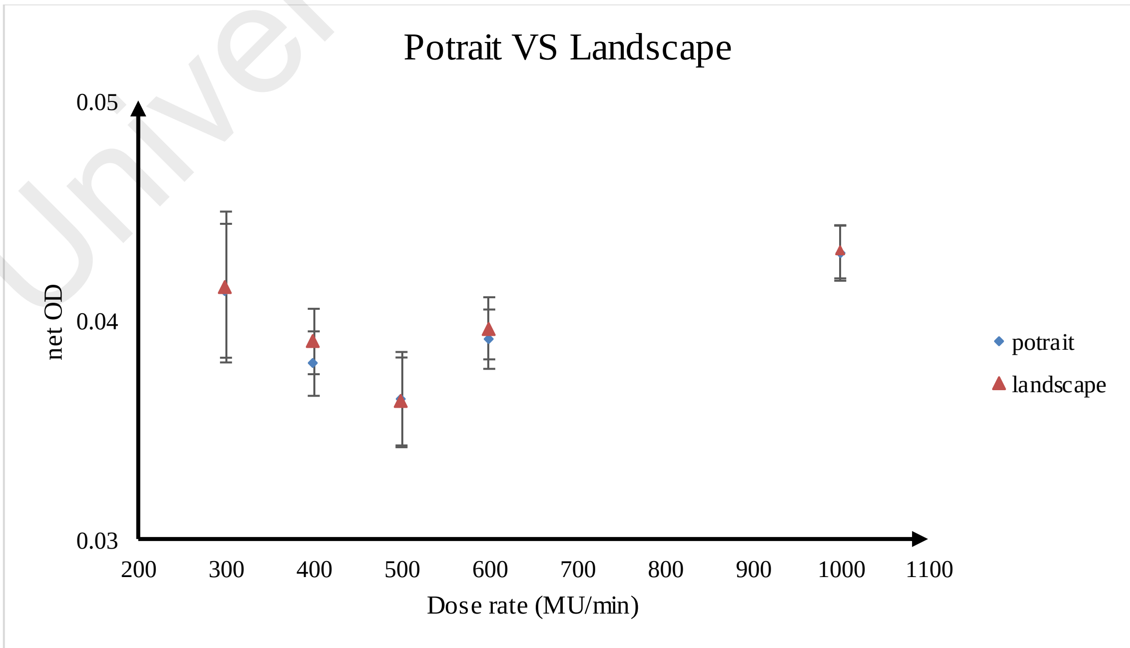


Figure 4.4: HD-V2 film scanning orientation relative to the scanner direction for 6 MV photon beam.

The deviation of net OD between face-up and face-down scanning orientation is within modest range of 0.05% to 2.53%. Figure 4.5 shows the graphical differences between face-up and face-down orientations for 6 MV photon energy. Error bars in the graphs representing 1 SD for the means of 3 reading films.

These results have shown that HD-V2 film has eliminated face-up and face-down dependency although it has unsymmetrical structure. This is probably because the films were irradiated at the depth of maximum dose (1.5 cm), where charged particle equilibrium (CPE) exists. Irradiation of films at this depth does not significantly affect the amount secondary electrons deposited on either surface of the film. It is hypothesized that the orientation of film, whether it is of face-up or face-down orientation will have an effect on the net OD produced at non-CPE region, for example on the phantom or patient surface. In any case, due to the asymmetrical structure of the HD-V2 film, it is recommended for the film to be scanned consistently with the same side of the film facing the light source regardless of whether landscape or portrait orientation is used in order to minimize the random errors.

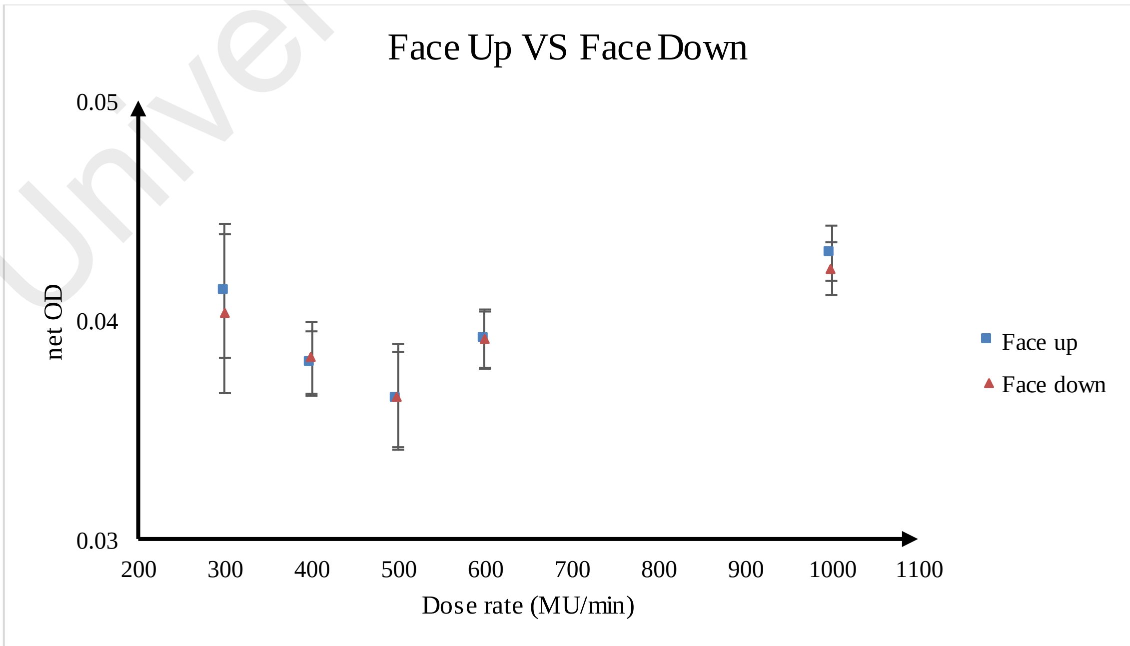


Figure 4.5: HD-V2 film scanning orientation facing the scanner light source for 6 MV photon beam.

4.5 Angular Dependence

The normalized value of net OD was plotted as a function of the incident radiation angles as shown in Figure 4.6. All the readings at different angles were normalized to the 0°, in which the film was perpendicular to the beam. Each point on the graph represents the average value of net OD of three films irradiated with the same set-up at a gantry angle. Error bars were too small to be observed from the graphs, representing 1 SD for the mean reading of 3 films. It can be seen that the variation in net OD was within the range of 0.001 to 0.002 net OD and with a percentage difference less than 4.3%.

The deviation of net OD was quantified using the Equation 4.5 below by taking gantry angle of 0° as control group.

$$\%\ \text{change in net OD} = \frac{net\ OD\ (0^0) - net\ OD\ (x^0)}{net\ OD\ (0^0)} \times 100\ \% \qquad \text{[Equation 4.5]}$$

Where, net $OD_{(0°)}$ = net OD of film irradiated perpendicular (90°) to the beam

net $OD_{(x°)}$ = net OD of film when irradiated at x° gantry angle

With the deviation in net OD of less than 4.3%, we can summarize that HD-V2 film is a good substitute in response to the clinical need for a radiation dosimeter with both high resolution and minimal angular dependence. This result shows that HD-V2 is the same with its precursors, EBT3 and EBT2 which show no angular dependence (Chan et al., 2009, Kairn et al., 2011).

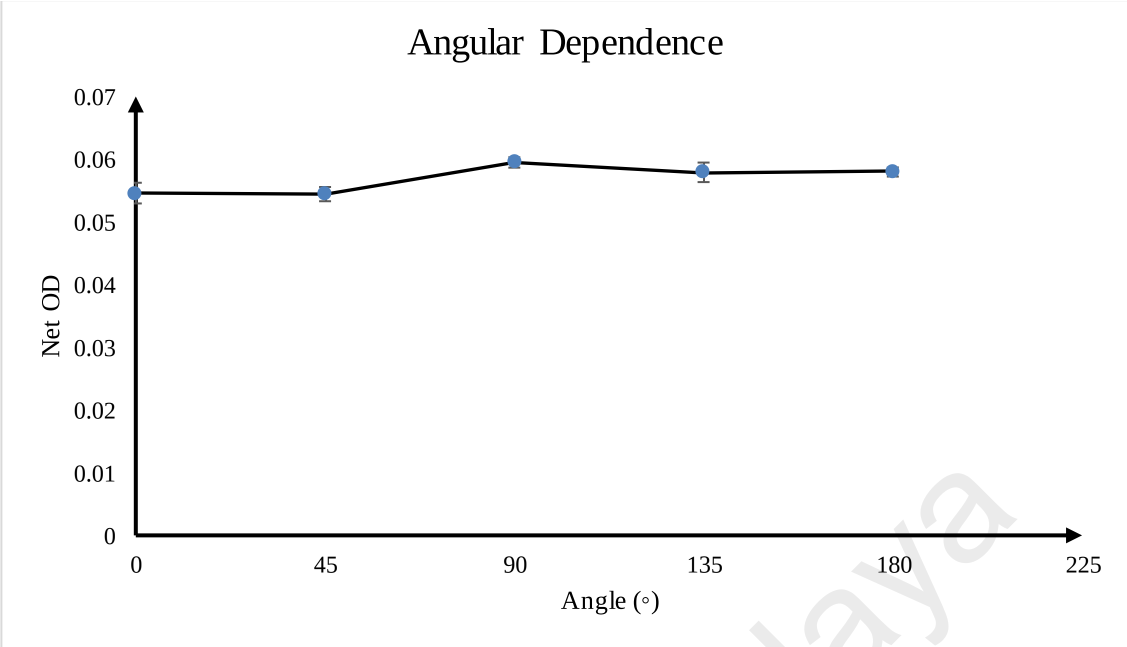


Figure 4.6: The angular dependence of HD-V2 film.

4.6 Dosimetric verification in Stereotactic Radiosurgery (SRS)

Table 4.3: The measurements of Gafchromic HD-V2 film and TPS predicted dose head and neck radiotherapy using SRS

Clinical Cases	Prescribed Dose (Gy)	Measured Dose (Gy)		
		TPS	HD-V2 film	Difference (%)
1	15	14.078	14.110	0.22
2	9	8.048	8.315	3.82

The comparison Gafchromic HD-V2 film measurements with the TPS predicted dose head and neck radiotherapy using SRS are summarized in Table 4.3. Both, in clinical case 1 and 2 measured dose by the HD-V2 film measured higher dose compared to the TPS predicted dose with deviation of within 0.22% and 3.82% respectively.

The International Commission on Radiation Units and Measurements (ICRU) recommended that the absorbed dose to the target volume be delivered should be less than ±5% of the prescribed dose (ICRU, 1993).

Meanwhile, the quality assurance of treatment planning system for radiotherapy by AAPM Task Group 53 and IAEA TRS 430 stated that the acceptable criteria for external beam dose calculation in a homogeneous phantom are within ±5 % and 5 mm (Fraass et al., 1998, IAEA, 2004).

In this study, the results of the point dose measurements for SRS treatment irradiations showed that the deviations between the TPS predicted dose and HD-V2 film measurements were less 4% which were within the recommended values. The comparison of doses measured for both cases show a good agreement with the recommendation value by ICRU and IAEA between the TPS predicted doses and the HD-V2 films.

The small different in dose measurement is due to the planning treatment set-up of the SRS. In SRS, steep dose gradient is a must due to the needed of accurate and precise radiation dose distribution delivered to the tumour and protect the surrounding healthy tissues from the high dose radiations are very important (Massillon, 2010). Thus, lead the TPS predicted slightly different dose compared to the dose measured by HD-V2 film due to the difference in the conformal region of the film in the plans created. Based on the result, we can conclude that the HD-V2 film and the TPS predicted dose have no significantly different and HD-V2 film can be used in dosimetric verification of SRS treatment quality assurance.

CHAPTER 5: CONCLUSION AND FUTURE WORK

Stereotactic Radiosurgery (SRS) precisely gives high dose of radiation (>10 Gy) to small tumour or lesion in one fraction. This study was about the investigation of HD-V2 film characteristics and its application for dosimetric verification in SRS. The physical characteristics of HD-V2 film for radiation dosimetry megavoltage photon energy range was characterized and its feasibility for the dosimetric verification of SRS treatment was quantified. The following conclusions and recommendations for HD-V2 film dosimetry were made.

In this first part of this study, the HD-V2 film calibration curve range from 0 - 100 Gy was established, thus make the film as absolute dose measurement. The film calibration was done using higher dose rate 1000 MU/min where SRS treatment is commonly used. In SRS clinical range of dose, HD-V2 film was found to be energy independent for high photon energies of 6 and 10 MV. In terms of dose rate dependency, an average deviation of less than 4.94% for all dose rates tested. This fulfils one of the primary criteria of ideal dosimeter by HD-V2 film, which is dose rate independence.

Although the structure of HD-V2 film is unsymmetrical, our study showed that there was no impact whether the film was in either "face-up" and "face-down" scanning orientation when irradiated at depth of maximum dose, with a deviation ranged from 0.05% to 2.52%. In addition, almost the same result was produced when tested for portrait and landscape scanning orientations HD-V2 film with deviation of net OD range less of than 2.7%.

However, precaution for scanning in both portrait with landscape as well as face up with face down scanning orientations is recommended by maintaining constant film scanning orientation from film calibration to its application for dosimetric verification in order to minimise the uncertainties. Film can to be marked before irradiation to ensure the true orientation. From the literature, HD-V2 film is recommended to be kept for at least 24 hours post irradiation before scanning as the readings in net OD of film are not constant and still increasing for a few hours.

For rotational radiotherapy technique such as SRS, other characteristic of HD-V2 film that needs to be considered is film angular dependence, with deviation of within less than 4.3%. The HD-V2 film was found to be angular independent which is similar to the characteristic of other generation of gafchromic films.

In the second part of this study, the Gafchromic HD-V2 film was used for dosimetric verification in SRS. Based on the result from this part of study, it is concluded that the EBT3 film is appropriate for treatment dosimetric verification in SRS with a good tolerance level of accuracy. A deviation from 0to 3.8% between calculation dose of TPS and verified dose by HD-V2 film is well within the tolerance limit of ±5% published by the ICRU and AAPM.

One of the suggested futures works on HD-V2 film is to establish calibration with different post irradiation development time to further increase the accuracy of film in dose measurement. Moreover, further investigation is needed to improve the passing rate tolerance with a SRS tolerance less than 1% and 1 mm can be adopted in dosimetric verification. It also suggested that, the film need more clinical case of SRS or even for SBRT that used high energy of radiation dose more of than 10 Gy for testing this film for dosimetric verification.

In this study, it was found that the film is not dependent on the 'face-up' and 'face-down' orientation. The measurement was performed with the film position at d_{max}, which is a region with CPE. It is proposed to repeat the same measurement at surface, at which it is hypothesized that the 'face-up' or 'face-down' orientation will impact the result of measurement.

Another future work to be done is by using multichannel method for film scanning, instead of using individual red or green channel. Based on (Ashland, 2012 the main characteristic of HD-V2 film in contrast to the predecessor generation HD-810 film is the integration of a yellow marker dye. We have loosed the used of triple-channel dosimetry that compensates for thickness differences of the film's active layer.

Last but not least, HD-V2 film dosimetry requires a very consistent procedure during films handling, irradiation, calibration, film scan and analysis in order to provide high accuracy and precision in radiotherapy dose distribution measurement.

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