DEVELOPMENT OF EXTERNAL BEAM THERAPY 3 ULTRAVIOLET DOSIMETER

by

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Thesis submitted in fulfilment of the requirement

for the degree of

Master of Science

June 2018

ACKNOWLEDGEMENT

First and foremost, allow me to express my deepest thanks to Allah SWT for giving me the strength and health to pursue my research study with full of perseverance and endurance. It is indeed a great opportunity for me to pursue my master research study in the School of Physics, USM.

My deepest gratitude to my supervisor, Dr. Ahmad Fairuz Bin Omar. I am fortunate to have a supervisor who gave me the freedom to explore my research study and thesis writing at my own freewill. He steered me in the right direction whenever he thought I needed it. He taught me how to question thoughts and express ideas. He also gives me encouragement, practical advice, commenting on my views and helping me understand and enrich my ideas.

I would also like to forward my humble thanks to the Dean's and staffs at School of Physics and Institute Postgraduate Studies (IPS) all this while for being cooperative and constantly helpful. My sincere thanks also to Mr. Mohtar Bin Sabdin, Assistant Science Officer for his cooperation in allowing me to use the equipment and carried out the experiments in the Engineering Physics Laboratory USM.

Nevertheless, I must express my very profound gratitude to my beloved parents and brother for providing the unfailing support, guidance and continuous encouragement throughout the process of my research study and thesis writing.

Finally, this study was financially supported by Ministry of Higher Education – Fundamental Research Grant Scheme (Grant No. 203 / PFIZIK / 6711491).

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LIST OF ABBREVIATIONS

Symbol / Abbreviation	Caption
^{o}C	Degree Celsius
^{o}F	Degree Fahrenheit
λ_{max}	maximum absorption peak at particular wavelength
λ_{ρ}	irradiance responsivity
Ω	ohm
AC-to-DC	alternating current-to-direct current
ADC	Analog-to-Digital Converter
AlGaN	Aluminium Gallium Nitride
CCD	charge-coupled device
cGy	centigray
CIE	International Commission on Illumination
CMOS	complementary metal-oxide semiconductor
DA	diacetylene
DC	direct current
EBT 3	External Beam Therapy 3
EUV	electronic ultraviolet
eV	electron volt
GND	Ground
HPLC	high pressure liquid chromatography
HS-NIRS	High Sensitivity Near Infrared system
I	Irradiance or intensity
IDE	Integrated Development Environment
IMRT	Intensity-modulated radiation therapy
kΩ	kiloohm

keV	kiloelectron volt
kV	kilovolt
LCD	Liquid crystal display
LDR	Light Dependent Resistor
LED	Light-emitting diode
LiPCDA	lithium salt of pentacosa-10,12-diyonic acid
MΩ	Megaohm
mJ/cm^2	milliJoules per square centimeter
mW/cm^2	milliWatts per square centimeter
MHz	megahertz
MPU	Motion Processing Unit
MS	Microsoft Windows
MV	Megavolt
m	Gradient
mA	milliampere
mcd	millicandela
Net ROD	net reflective optical density
netOD	net optical density
NTU	Nephelometric Turbidity Unit
OD	optical density
OF-NIRS	Optical Fiber Near Infrared Spectroscopy system
OF-NIRS-M	Optical Fiber Near Infrared System-Modified
OF-RGB	optical fiber red-green-blue system
OF-RS	optical fiber red system
PADC	polyallyldiglycol carbonate
PDA	polydiacetylene
PMMA	Poly (methyl methacrylate)

PPO	Polyphenylene Oxide or poly 2,6-dimethyl-1,4-phenylene oxide
PS	polysulphone
PT	phototransistor
PWM	Pulse Width Modulation
pH	Potential of hydrogen
R	correlation coefficient
R^2	coefficient of determination
RGB	Red-green-blue
RH	relative humidity
RMSE	root-mean-square error
S_{ery}	erythermal UV dose
S_g	Global solar radiation
SPF	Sun protection factor
TAOS	Texas Advanced Optoelectronic Solutions, Inc.
USB	Universal Serial Bus
USM	Universiti Sains Malaysia
UV	Ultraviolet
UVI	Ultraviolet irradiance
UVR	Ultraviolet radiation
V	voltage
Vcc	voltage common collector
V_{DD}	drain supply
V_{IN}	input voltage
V_{OUT}	output voltage
VMAT	volumetric modulated arc therapy
WHO	World Health Organization

PEMBANGUNAN DOSIMETER ULTRAUNGU TERAPI ALUR LUARAN 3

ABSTRAK

Sinaran ultraungu (UV) suria diketahui berpotensi membawa kesan buruk kepada kesihatan manusia apabila terdedah dalam jangka panjang. Oleh itu, rutin pengukuran dos UV sinaran suria yang terdedah adalah penting. Kaedah yang ada dalam menentukan pendedahan UV suria adalah melalui meter UV. Masalah yang terdapat dalam kaedah ini ialah ia hanya boleh membenarkan pengukuran titik tunggal (iaitu, intensiti UV serta-merta) dalam mW / cm². Ini bermakna ia tidak mencatatkan dos UV terkumpul pada satu masa. Jadi, untuk instrumen ini beroperasi, ia memerlukan pendedahan berterusan kepada persekitaran luar yang boleh menyebabkan kerosakan kepada instrumen disebabkan oleh terlalu panas. Selain mengambil masa, penggantian peranti yang rosak juga menambah kos. Oleh itu, kajian ini mencadangkan kegunaan filem Gafchromic EBT3 kerana dapat merekodkan dos UV terkumpul, pakai buang, mudah alih dan mempunyai korelasi yang baik dengan UV. Selain itu, instrumen diperlukan untuk mentafsirkan pengumpulan dos (iaitu, perubahan warna) dari filem EBT3 selepas pendedahan. Tetapi, instrumen yang biasa digunakan untuk mentafsir perubahan warna filem masih bergantung pada kaedah konvensional (iaitu pengimbas dan spektrometer) di mana peranti ini sangat besar, mahal dan pengguna akhir memerlukan aplikasi perisian untuk menganalisis lebih lanjut maklumat warna dari filem. Oleh itu, penyelidikan ini telah membangunkan 'EBT3 UV Dosimeter' berasaskan 10-bit pengawal mikro (dalam unit mJ/cm²) yang terdiri daripada satu pemancar cahaya diod (LED) dengan panjang gelombang pelepasan puncak pada 634.89 nm sebagai sumber cahaya dan fotodiod transimpidensi sebagai sensor. Dosimeter ini dengan serta-merta boleh menentukan dan memaparkan

UV-A dan B suria dos dalam mJ/cm². Sebelum pembangunan sistem, analisis kuantitatif menerusi penggunaan sistem spektroskopi yang jelas dan LED-fotodiod berasaskan pengukuran optik telah dijalankan pada set 50 sampel EBT 3 dengan tambahan dos (pendedahan) UV suria. Experimen ini telah membuktikan keunggulan panjang gelombang sekitar 635 nm dalam menentukan perubahan warna filem EBT3. Alat 'EBT3 UV Dosimeter' yang baru dibangunkan dapat menghasilkan kalibrasi yang tinggi dan ketepatan ramalan untuk pengukuran dos UV suria sehingga 32000 mJ/cm2 masing-masing dengan koefisien determinasi, $R^2 = 0.9954$ dengan akar rata-rata kesalahan kuadrat (RMSEC) = 656.703 mJ/cm² dan $R^2 = 0.9963$ dengan RMSEP = 470.904 mJ/cm². Hasil kebolehulangan pada sisi lain menghasilkan $R^2 = 0.9966$ dengan RMSE 528.795 mJ/cm².

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ABSTRACT

Solar ultraviolet radiation is well known to potentially brings harmful effect to human health when exposed in a prolong nature. Hence, the routine measurement of exposed solar ultraviolet (UV) dose is essential. The existing method in determining solar UV exposure is through UV meter. The problem found in this method is that it can only allow a single point measurement (i.e, an instantaneous UV intensity) in mW/cm². This means it does not record accumulative UV dose at one time. So, for this instrument to operate, it requires continuous exposure to outdoor environment which may cause defect to the instrument due to overheating. Besides time consuming, the replacement for the defective device also added to the cost. Thus, this research proposed the use of Gafchromic EBT 3 film as it can record accumulative UV dose, disposable, mobile and have good correlation with UV. Besides that, an instrument is needed to interpret the accumulation of dose (i.e, color changes) from EBT 3 film after exposure. But, the commonly used instruments to interpret the color changes of the films are still relying on conventional methods (i.e. scanner and spectrometer) where these devices are bulky, expensive and the end user needs a software application to further analyze the color information from the film. Therefore, this research has developed a 10-bit microcontroller based EBT 3 UV dosimeter (in mJ/cm²) that comprised of a single light-emitting diode (LED) with a peak emission wavelength at 634.89 nm as the illumination light source and a transimpedance photodiode as the sensor. This dosimeter can instantly determine and display solar UV-A and B dose in mJ/cm². Prior to the development of the system, a quantitative analysis through the

application of visible spectroscopy system and LEDs - photodiode based optical measurement has been conducted on a set of 50 EBT 3 samples with incremental solar UV (exposure) doses. This experiment has proven the superiority of the wavelength around 635 nm in quantifying the color changes of EBT 3 films. The newly developed EBT 3 UV dosimeter manage to generate high calibration and prediction accuracy for the measurement of solar UV dose up to 32000 mJ/cm^2 with coefficient of determination, R^2 = 0.9954 with root mean square error (RMSEC) = 656.703 mJ/cm^2 and R^2 = 0.9963 with RMSEP = 470.904 mJ/cm^2 respectively. The reproducibility results on the other hand produces R^2 = 0.9966 with RMSE 528.795 mJ/cm^2.

CHAPTER 1: INTRODUCTION

1.1 Introduction

There are various applications of UV radiation (UVR) that provides benefits to the people such as in dental medicine (i.e, bacterial infection in root canal walls) (Panov & Borisova-Papancheva 2015), treatment of jaundice (Siegfried et al. 1992), water disinfectant, airborne microorganisms' decontamination (Guerrero-Beltrán & Barbosa-Cánovas 2004), microbial inactivation on fruits, food and beverages (Turtoi 2013; Turtoi & Borda 2013) and forensic analysis in fingerprints detection (Akiba et al. 2007). Nonetheless, there are also implication of UVR to human health. As we know, everyone is exposed to UVR from the sun either while the person is walking, doing outdoor activities, or even while staying in a building that have windows. The depletion of ozone layer is a known factor to cause higher UVR irradiance towards the earth surface and as a result, potentially brings harmful effect to human health. World Health Organization (WHO) stated that large doses of UV-A can cause premature ageing, higher doses of UV-B can cause sunburn while UV-C does not reach the earth surface, so, not normally considered as a risk factor for skin cancer, however, UV dose also important for the production of vitamin D for skeletal disease such as rickets and osteoporosis (World Health Organization 2016b). Realizing the adverse effects that excessive UV dose may cause, the monitoring of UV dose is therefore important.

Irradiance (or intensity) (I) is defined as a power received by a surface per unit area and per unit time which is when any kind of radiation (radioactive particles from a source, or electromagnetic waves) is incident on a surface (BBC 2018). Thus, ultraviolet irradiance (UVI) is the measure of UV radiation (UVR) power received by a surface per unit area and per unit time, usually expressed in Watts or milliWatts per square centimeter (W/cm^2 or mW/cm^2, respectively). Meanwhile, dose or exposure is the quantity or amount of ionizing radiation received or absorbed by the surface (Ionactive 2017). Therefore, solar UV dose is the measure of sunlight UVR power received by a surface per unit area, multiplied by the amount of time the surface is exposed to this power and is represented in the unit of Joules or milliJoules per square centimeter (J/cm^2 or mJ/cm^2, respectively) (Fluidquip Australia 2009) or can also be defined as irradiance integrated over time. In a simple definition, solar UV dose is the amount of UVR received or absorbed by the surface according to the amount of time the surface is exposed to sunlight.

Since UVR exposure have shown a significant impact on human wellbeing, whether under or over doses, its monitoring is thus important. The measurement of solar UVR allows early preventative measure to be made. There are several UV radiation measuring instrumentations commercially available. However, due to the product limitations, since the last decade, researchers start to evaluate the potential of External Beam Therapy (EBT) film in measuring ultraviolet dose. EBT film is originally designed for the measurement of absorbed doses of ionizing radiation and suitable for high-energy photons and normally used in Intensity-Modulated Radiation Therapy (IMRT), volumetric modulated arc therapy (VMAT) for treatment of cancer (Ashland Inc. 2018). Many researches have successfully characterized the relationship and direct correlation between the color changes of EBT films with solar ultraviolet dose. For this reason, this research is dedicated in examining in detail the potential of latest version of EBT film (EBT3) in measuring solar UV dose and introduced a specialized instrument to quantify the color changes of the films (in relation to different UV doses that it absorbs).

1.2 Problem Statement

The existing method in determining solar UV exposure is usually through UV meter. The UV meter is an instrument that measures UV irradiance (i.e. an instantaneous UV intensity) in the unit of mW/cm^2. For this instrument to be used in the measurement of UV dose, this instrument requires a continuous exposure to outdoor solar irradiance which gradually may cause defect to the instrument due to overheat. The replacement for the defective device also added to the cost and time consuming. Pyranometer, on the other hand can be used as UV dosimeter during the clear sky, but uncertainties in measurement becomes larger under cloudy sky condition (Seckmeyer et al. 2012). Besides, the application of these instrumentations only allows a single point measurement to be made. Therefore, this research proposed the application of Gafchromic EBT 3 film as a potential replacement for UV meter and pyranometer due to the limitation found on these devices. This film can record accumulative UV dose, disposable, mobile and have good correlation with UV.

The color information from the EBT3 films needs to be extracted and correlated with the actual UV exposure dose. Based on the current literature (until mid-2018), the commonly used instruments to interpret the color changes of the films are flatbed scanner through RGB imaging techniques and visible spectrometer through absorbance spectroscopy technique. The disadvantages of these devices are they bulky and expensive. Besides, the end user needs a software application to further analyze the color information from the film. Thus, in this research, 10-bit EBT3 UV Dosimeter is designed based on the application of light emitting diode (LED) and photodiode as a potential replacement for flatbed scanner and spectrometer. This dosimeter is specialized for the measurement of EBT 3 film discoloration to instantly determine and display solar UV-A and B dose in mJ/cm^2.

1.3 Scope of Study

This research is mainly focus on the development of low cost EBT3 UV Dosimeter that use only LED and photodiode principle with other supporting circuitry specialize for the measurement of EBT 3 film discoloration in relation to accumulative solar UV-A and UV-B dose. To support the selection of peak emission wavelength of LED for the newly developed system (EBT3 UV Dosimeter), two experiments have been carried out. Spectroscopy based system and LED based system is used to determine wavelength that response the best towards the color changes of EBT 3 films. The spectroscopy-based system has broad spectral response range that covers visible region between 400 and 700 nm. Meanwhile, LED based system utilized multiple wavelength LEDs as its light source and photodiode as its detector. Besides, uses Arduino Integrated Development Environment (IDE) software which is the simplified version of C++ programming for data processing and display. Segmentation technique was employed to the developed calibration algorithm to improve the measurement accuracy of the dosimeter. The EBT3 UV Dosimeter is capable of measuring UV dose up to 32000 mJ/cm^2 with resolution of 657 mJ/cm^2.

1.4 Research Objectives

The objectives of the study are as follow:

1. To develop specialized EBT3 UV Dosimeter for the measurement of solar UV-A and B dose (mJ/cm^2) through the discoloration of EBT 3 films.
2. To profile the peak response wavelength of the EBT 3 films using visible absorbance spectroscopy technique and using LEDs – photodiode based optical measurement.

3. To apply segmentation technique in improving the accuracy of calibration algorithm for the application in specialized EBT3 UV Dosimeter.

1.5 Significance of Study

The color changes of EBT 3 film is known for its high correlation with UV exposure. EBT3 records the UV reading as accumulative dose (in mJ/cm^2) instead of irradiance (in mW/cm^2) and allows spatial UV dose measurement to be made. This is an important feature of film-based dosimetry since it enables several readings to be taken simultaneously and hence, provide us with better understanding on the distribution of UV exposure across an area or region. The use of film-based dosimetry also allows the measurement of UV to be taken underwater, which is useful for the study on the impact of UV dose on aquatic life. This research also presents a critical analysis on the films characterization through colored LEDs (i.e. with peak emission wavelength within visible region). This is done to ensure the ability of low cost LED-photodiode based system to reproduce the measurement accuracy obtained through visible spectroscopy system. Most importantly, this research has successfully presented an innovative 10-bit EBT3 UV Dosimeter with high accuracy of solar UV A and B measurement. The introduction of the new system eliminates the need of post data processing, as conventionally required for the film measurement using scanner and spectrometer.

1.6 Structure of the Thesis

This thesis consists of five chapters. First chapter provides an overview of this study, problem statement, scope of study, research objective, and significance of this study. Literature review will be covered in Chapter two which include some current works by researcher. Chapter three will be explained how the experimental set-up, experimental procedure, and equipment used for this project. Chapter four presents all the results of this research with discussion and how the result being analyzed. Chapter five summarizes all the output and result of this research with recommendation for future study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter introduces background study of solar UVR and instrumentation that are commonly used for solar UVR measurement. The discussion on Gafchromic film is also covered within this chapter, particularly on its properties. The next section review on the application of EBT 3 film that include its application in measuring ionizing radiation and UV radiation as well as methods in measuring color changes of Gafchromic film. Furthermore, this chapter also included literatures on various research work on the existing application of LED-photodiode system. Finally, the theoretical explanation on Beer-Lambert's Law will be discussed in the last part of this chapter.

2.2 Solar Ultraviolet Radiation

2.2.1 Background Study

The solar UV spectrum comprises of different wavelength ranges, including UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (100-280 nm) (International Organization for Standardization 2007). When UV rays from sun reach to the earth's surface, the result of the amount of UV dosage varies from one place to another and also by the different in time (Allen 2001). Amongst several distinguish factors are the appearance of the cloud, ozone in the stratosphere, oblique angle of sunlight reaching the earth surface, aerosols in the troposphere, water depth and elevation that plays an important role in causing the radiation effect. Stratosphere is the second layer of the earth atmosphere. It is a layer in the sky that consists of lower boundary (tropopause), upper boundary (stratopause) and the ozone layer. The next higher layer above the stratosphere is mesosphere (Carnicom 2016). This can clearly be seen in Figure 2.1.

This ozone layer consists of oxygen molecule which is relatively abundant as it functions is to absorbs energy from incoming ultraviolet radiation from the Sun. The energy percentage of sunlight at the earth's surface is around 52 to 55 percent infrared (above 700 nm), 42 to 43 percent visible (400 to 700 nm), and 3 to 5 percent ultraviolet (below 400 nm) (Allen 2001). The UV radiation reaching the Earth's surface is made up of mostly UV-A which is 95% and with a small amount of UV-B which is only 5% whereas UV-C does not penetrate the earth surface because of absorption of ozone layer (which is the combination of three oxygen atoms into a single molecule (O_3)) and at atmosphere (consist of water vapour, oxygen and carbon dioxide) (IARC 2012; World Health Organization 2017a). Overexposure of UV-A can cause skin ageing and wrinkling due to the UV ray which can penetrate the deeper layer of the skin, UV-B cannot penetrate beyond the superficial skin layer which can cause sunburn (erythema) and burning. Both overexposure to UV-A and UV-B can cause skin cancer if prolonged under the sunlight (World Health Organization 2016a). Sufficient of UV exposure is necessary to produce Vitamin D which is essential for bone health. Insufficient UV exposure would result in skeletal disease (rickets and osteoporosis) from vitamin D deficiency. Overexposure to UV will result in skin cancer, malignant melanoma, sunburn (erythema) and cataract (Lucas et al. 2006; Belkin et al. 1994).

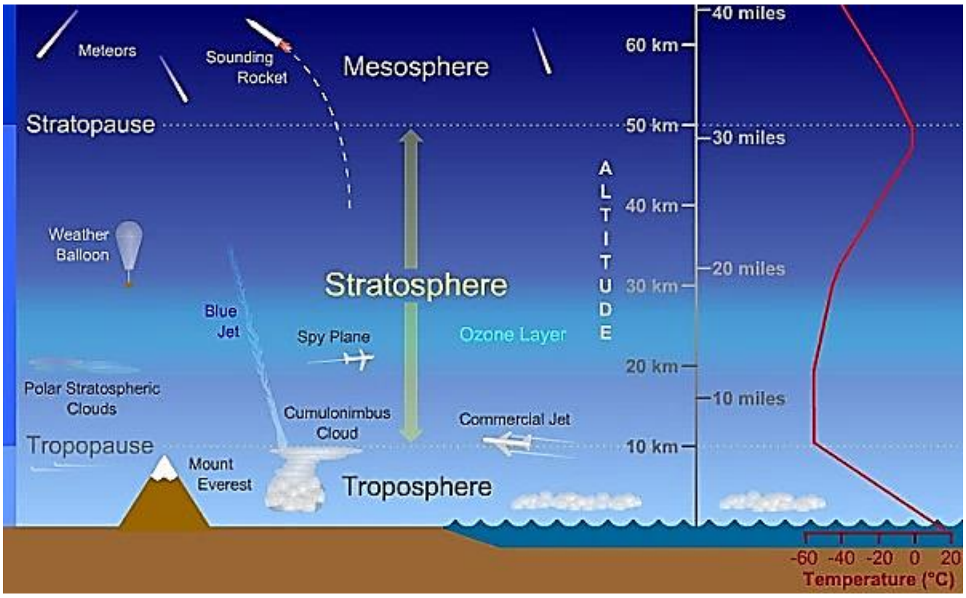

Figure 2.1 Layers of earth's atmosphere (Carnicom 2016)

2.2.2 Solar Ultraviolet Measurement

There are several types of dosimeters used in the measurement of solar ultraviolet dose such as electronic ultraviolet (EUV) dosimeter, polysulphone (PS) dosimeter, Polyphetylene Oxide (PPO) Film and personal UVR dosimeter. (Allen & McKenzie 2005; Allen & McKenzie 2010) developed EUV dosimeter badges in New Zealand and make a study about the EUV dosimeter badges apply on skiers, outdoor workers, school children that go swimming. It used aluminium gallium nitride (AlGaN) photodiode as a radiation sensor to measure UV dose (i.e, measure personal erythemal UV dose). (Allen & McKenzie 2010; Seckmeyer et al. 2012) stated that the EUV dosimeters can also receive UV irradiance to be measured as a function of time which the data on cumulative individual exposures and dose rates can be calculated later due to the data stored in the on-board memory (EEPROM memory-chips) that can be extracted via USB cable which can be run under Microsoft Windows (MS) for further analysis. (Allen & McKenzie 2005; Allen & McKenzie 2010; Seckmeyer et al.

2012) explained that EUV dosimeters are small and lightweight which can be attached to the body using a wrist or arm strap. The best match to the erythema action spectrum stated by the International Commission on Illumination (CIE) is obtained using an aluminium fraction of approximately 27% which is important for the spectral response of the AlGaN material across the UV spectrum (Swift et al. 2010). The disadvantage found by (Seckmeyer et al. 2012) about EUV dosimeters are this device show a bandpass mismatch when compared with the CIE erythema action spectrum that can vary between devices and their angular response also differs from the ideal cosine response. However, it can still be improved by carefully preselection of AlGaN detectors with lowest visible response and the closest match to the CIE because ideally, the spectral response of AlGaN detectors should show a close match with CIE erythema action spectrum and no response to visible irradiation (Seckmeyer et al. 2012).

Apart from that, (Parisi & Turnbull 2006) stated that PS dosimeters fabricated from PS in a form of thin film. PS film undergo photodegradation when exposed to UV radiation wavelength shorter than approximately 340 nm. The PS in thin film is formed by dissolving PS pellets in chloroform and pouring the solution on a polished glass slab. (Seckmeyer et al. 2012) stated that the PS dosimeters are lightweight, cheap, simple to handle and have a good thermal stability. However, (Seckmeyer et al. 2012; Webb 1995) mention that this device is not able to be used overextended measuring periods (i.e, able to record cumulative exposure dose over a small range, not more than 2 days as stated by (Schouten et al. 2007)). This requirement is important in measuring cumulative doses and dose rates in long term studies. To increase the amount of cumulative exposure dose measured, the PS films need to be replaced regularly. Because of that, researcher need to be on site almost every day (Schouten et al. 2007).

The PS dosimeter need to be replaced due to the saturation effects. The saturation effect causes the lack of temporal resolution of PS dosimeters (Siani et al. 2008). Apart from that, it is a time-consuming dose extraction methods (Webb 1995; Seckmeyer et al. 2012). Nevertheless, (Parisi & Kimlin 2004) have solved the problem by developing the filtered PS dosimeter system. This dosimeter can measure erythemal (sunburn or skin reddening) UV exposure over 3 to 6 days (extended dynamic range) at a subtropical side without replacing the dosimeter compare to unfiltered PS dosimeters. But, (Seckmeyer et al. 2012) compare and conclude that EUV dosimeters are more reliable compare to PS dosimeters. (Seckmeyer et al. 2012) also conclude that EUV and PS dosimeters can be useful to estimate personal UV exposures but cannot be considered as an inexpensive replacement for meteorological grade instruments (i.e, spectroradiometer).

Personal UVR dosimeter is the unexposed EBT 3 film place on top of fixed smiley-face graphic that corresponds to maximum suggested dose of UVR before erythermal response (sunburn or skin reddening). When this device is taken outside, the unexposed EBT 3 film change color slowly until become the same color as that fixed smiley-face graphic. This indicates that the user need to stay away from the sun (Francois et al. 2012). Previous studies have shown that the polyphenylene oxide (PPO) film have been widely used and capable of measuring long-term cumulative amounts of UV exposure with dynamic range much greater than PS dosimeter (Lester et al. 2003; Turnbull & Schouten 2008; Schouten et al. 2008; Schouten et al. 2007). Due to the problem found with PS dosimeter which unable to record cumulative UV dose in large range, (Schouten et al. 2007) purpose that PPO film would be the ideal to be used at marine locations for neglected measurement over huge amount of time. This type of dosimeter was fabricated from poly 2,6-dimethyl-1,4-phenylene oxide

(PPO) film for solar UV measurement in underwater use and in dry land environment (Schouten et al. 2010; Schouten et al. 2007). Schouten and his colleagues study the dose response, cosine response, exposure additivity and watermarking effect of PPO dosimeter in underwater environment. As well, study on the overnight dark reaction and UV-A and visible radiation response of PPO dosimeter. All this study is important for the use of the error correction to improve the reliability of the UV data measured by the PPO dosimeters. Schouten et. al concluded that PPO dosimeter is possible for underwater UV exposure measurements over a long period of time (Schouten et al. 2007).

Several researchers have utilised instruments such as pyranometer and UV meter for the measurement of solar UV irradiance. Pyranometer can be used for outdoor global solar radiation, S_g (mixture of direct and diffuse solar radiation) in units W/m^2 and need to be placed under unobstructed natural daylight conditions (Journée & Bertrand 2010; LI-COR 2018b). This instrument operates at range from 305 to 2500 nm (Seckmeyer et al. 2012). S_g is the combination of direct (i.e, passes directly through the atmosphere to the earth surface), diffuse (i.e, scattered in the atmosphere) and reflected (i.e, reaches the surface and reflected to near surface) solar radiation. S_g occur at wavelengths between 300 and 3000 nm, including UV (300-400 nm), visible (400-700 nm), and infrared (700-3000 nm) radiation (LI-COR 2018a). (Journée & Bertrand 2010) performed measurement at Uccle using CM11 Pyranometer which gain the daily values in J/m^2 from 10 and 30 min data. In addition, (Seckmeyer et al. 2012) state that pyranometer can be used as UV instrument which is possible to provide acceptable results during a clear sky but when in cloudy condition, the uncertainties become much larger. Based on (De Bock et al. 2014) paper, the cloudless sky will enhance scattering and hence, results in the increase of erythermal UV dose (Sery) and mixture of direct and diffuse solar radiation (Sg). Moreover, UV meter is a device that can detect UV light in a broad range of sensitivities (Ellis & Harris 2017). There are a lot of UV meters manufactured with its specification based on the multipurposed usage (Solarlight Company INC. 2018). A UV meter is typically a small, portable device that produces a digital reading based on data taken by the sensors (Ellis & Harris 2017). Normally, the UV meter provides an indication of the level of UV radiation on the need for sun protection as shown in Figure 2.2 to avoid negative consequence such as skin damage risk (Cancer Council Western Australia 2018a).

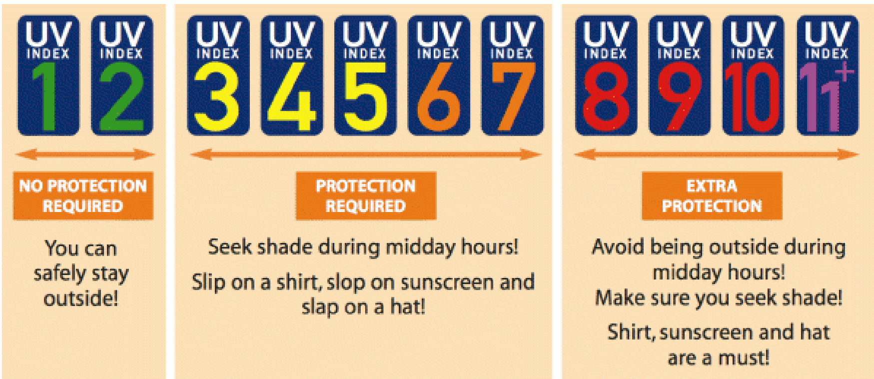

Figure 2.2: UV index level for sun protection (Cancer Council Western Australia 2018b)

In a related example, UV meter has been used by (Yusof et al. 2016) to study the irradiance of UV LEDs with two different peak emission wavelengths which is 365 and 375 nm. (Tajuddin & Omar 2017a) on the other hand, used UV meter model YK-35UV in measuring solar ultraviolet exposure on EBT3 films. The UV meter can detect total UVA and UVB irradiance. The UV meter contains UV detector with effective spectrum between 290 and 390 nm and with two distinctive range of measurements and resolutions; 2 mW/cm² (1.999 mW/cm² × 0.001 mW/cm²) and 20 mW/cm² (19.99

mW/cm² × 0.01 mW/cm²). The UV meter has also been used in museum, as part of preventive measures to protect the parchment, canvas, paints, and other art-related materials from damaged by the UV light. The UV readings are monitored regularly using UV meter to ensure that the UV levels have not changed and reaching dangerous level (Ellis & Harris 2017). UV light is regularly used in industries for microorganisms' disinfectant in food, water, medical tools and air purifier. Hence, operators are required to check the emitted rays produced by the UV sterilizer is at acceptable level for sterilization using highly sensitive UV meter (OAI Instruments n.d.).

In addition, there is a study on solar ultraviolet radiation under un-obstructed and obstructed UV environments in a sub-tropical urban environment. The UV radiation can be influenced by air pollution (high aerosol loadings) and high-rise buildings. The results show that the total UV (UVA+UVB) radiation reduced in high-rise buildings and narrow road. The un-obstructed exposure rate found in the open area surrounded by 20-storey buildings is not more than 80% (Wai et al. 2015). (Wai et al. 2017) verify that the building obstruction cause the huge reduction of total solar UV exposure in the unblock exposure. They also identify that the total solar UV exposure rate caused by the-reflection of reflective curtain walls from the building that reach the ground level (un-obstructed area) is 23%. Thus, this indicates that the improper building design will create additional harmful effects of solar UV radiation on the environment (Wai et al. 2017).

2.3 Gafchromic Films

There are numerous form of radiochromic dosimeters such as liquids, gels, films and pellets (Williams & Metcalfe 2011). In this research, the radiochromic dosimeters used is a film-based dosimeter, specifically known as Gafchromic EBT 3 film. Generally, radiochromic film has become an important tool to verify dose distributions in highly conformal radiation therapy such as IMRT, VMAT, X-ray. Since the last decade, more researches are being conducted on the applicability of various types of radiochromic film in measuring UV radiation dose.

2.3.1 Properties of Gafchromic films

The cross-sectional structure of Gafchromic EBT, EBT 2 and EBT 3 films are shown in Figure 2.4 a (Devic et al. 2012), b (Ashland n.d.) and c (Ashland Inc. 2018) . EBT, EBT 2 and EBT 3 have same active component and response in the active layer but the difference is EBT 2 and EBT 3 have a yellow dye added to the active layer compare to EBT (Butson et al. 2009; Reinhardt et al. 2012; Williams & Metcalfe 2011). In addition, EBT has double active layer but EBT 2 and 3 have single active layer with same thickness. This shows that EBT 2 and 3 have a slightly narrower active layer than EBT (Williams & Metcalfe 2011). The atomic composition in EBT 2 and EBT 3 are different from EBT but EBT 2 and 3 have same atomic composition (Reinhardt et al. 2012; Brown et al. 2012; Williams & Metcalfe 2011). The EBT 3 is symmetrical while EBT 2 is asymmetric. EBT 3 is symmetrical in the sense that the single active layer of EBT 3 film is symmetrically sandwiched between two identical matte polyester layer substrates laminates with a special surface treatment containing microscopic silica particles that maintain a gap between the film surface and the glass window in a flatbed scanner. Thus, the formation of Newton's Rings interference patterns that found in EBT 2 film during film scanning using flatbed scanners is prevented (Ashland n.d.; Brown et al. 2012). The other purpose of symmetrical layer is to eliminate front and back side orientation dependence that found in EBT 2 film which means that the film can be scanned on either side (Ashland n.d.; Williams & Metcalfe 2011; Borca et al. 2013a; Reinhardt et al. 2012; Butson et al. 2009; Brown et al. 2012). The physical coloration of original film, EBT film has clear color while EBT 2 has distinct yellow color. The distinct yellow color of EBT 2 film is due to the added of yellow dye in active layer. Furthermore, EBT film started as a clear to light blue shade before irradiation and changed to a distinct blue color after irradiation while EBT 2 started as a very distinct yellow color before irradiation and changes to a green color after irradiation (Butson et al. 2009).

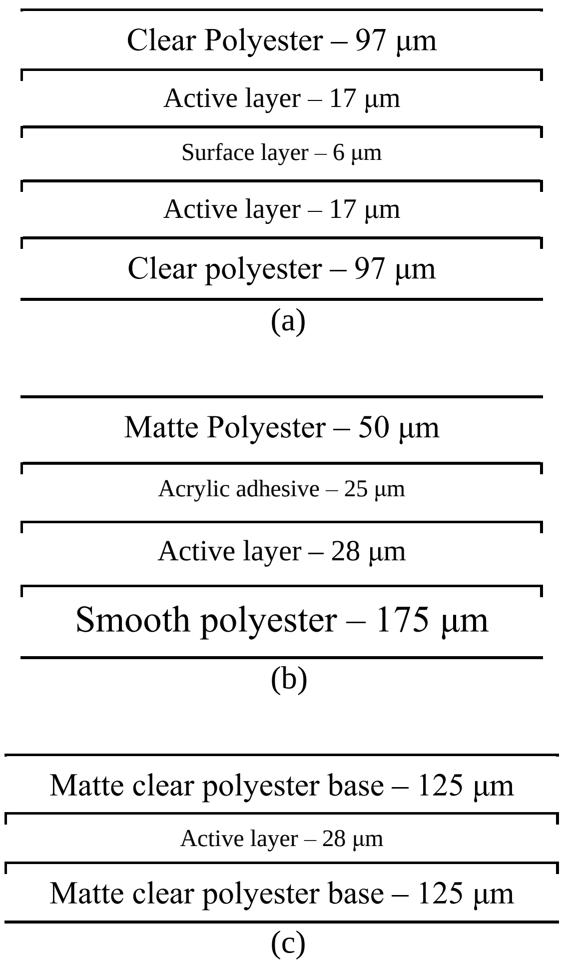

Figure 2.3 Structure of Gafchromic (a) EBT (Devic et al. 2012), (b) EBT 2 (Ashland n.d.), (c) EBT 3 (Ashland Inc. 2018)

Radiochromic dosimeters are solid state detectors which is the structural properties of their crystalline solid undergo polymerization result in a chromatic (color) change when exposed to radiation. The active component in active layer of radiochromic film (EBT, EBT 2 and EBT 3) responsible for the coloration are known as crystalline diacetylenes monomer as shown in Figure 2.5 (Lewis 2014; Williams & Metcalfe 2011). This crystalline diacetylenes monomer undergo polymerization, turning blue or red color depending on their specific composition each crystalline diacetylenes monomer type (Kalef-Ezra 2015). The crystalline diacetylene monomer used in EBT, EBT 2 and EBT 3 film is the lithium salt of pentacosa-10,12-diyonic acid (LiPCDA). This diacetylene monomers undergo a 1,4-polymerization upon exposure to heat, UV or ionizing radiation which join-up aligned and changes from colorless monomer to colored polymer chains that grow in length with level of exposure as shown in Figure 2.6 (Kalef-Ezra 2015; Williams & Metcalfe 2011) which will result in the increase of the film darkness (Lewis 2014) as illustrated in Figure 2.7. This has been proven by (Callens et al. 2017) paper which show that the increasing polymer concentration with radiation dose is successfully described by the modified single-hit model using a log-normal distribution for the length of the stick-like monomer microcrystals. Meanwhile, (Aydarous et al. 2013a) verified that based on the experimental results produce, color of the EBT3 films turns green during UVR exposure, and the darkness of the exposed film increases with UVR dose (exposure). This is also confirmed by (International Specialty Products 2010), where, the exposed EBT 3 film will appear green to the human eye due to the presence of the yellow marker dye in the active layer. (Aydarous et al. 2013a) also stated that the color change indicates that the active layer of the EBT 3 films is undergo chemical modifications under exposure to UVR, either by polymerization of the poly-diacetylene monomer or by photo-degradation of the formed polymers. The formed polymeric chains known as polydiacetylene dye polymers are responsible for the strong optical absorption. Normally, they are blue in color, and hence cause the film to absorb light in the red part of the visible spectrum (Williams & Metcalfe 2011; Kalef-Ezra 2015; Soares et al. n.d.).

Also stated by (International Specialty Products 2010), the blue colored polymer is formed when the active component in the film is exposed to radiation with absorption maxima at about 636 nm and 585nm. Since the highest peak absorption in the exposed film occurs at about 636 nm, with a secondary peak at about 585 nm, this shows that the greatest response occurs when measurements are made with red light. The peaks are due to the formation of a dye polymer from the radiolysis of the active component.

The statement above about the chromatic properties of Gafchromic EBT 3 films based on the chemical nature of LiPCDA monomer is confirmed by (Callens et al. 2015). The polydiacetylene (PDA) molecules is formed when interaction with ionizing radiation. (Callens et al. 2015) also verify that when radiation dose increasing, the EBT 3 films become optically less transparent due to the polymerization of diacetylene (DA) monomers once exposed to radiation. The monomer is LiPCDA which is colorless long-chained molecules. LiPCDA monomers are arranged in ordered microcrystals which are spread in the active layer of the film which has typical thickness of 28 μm. The monomer polymerized and form a linear long chained polymer (polyPCDA) with alternating double and triple carbon-carbon bonds in the backbone and the backbone absorbs light in the visible part of the spectrum. The polyPCDA concentration increases with increasing dose and becomes increasingly dark.

The polyPCDA (polymerized polymer) can exhibit at least three distinct color phases which are the bluish-green phase, blue phase and the red phase due to their appearance as explained by (Callens et al. 2015). The results show that the OD increases with increasing dose at all wavelengths which shows decreasing transmittance or increasing absorption and the two distinct peaks can be observed at 635 and 585 nm by spectrometer. (Callens et al. 2015) concluded that the two types of polyPCDA polymers found in the active layer of EBT 3 film are a blue phase (635 nm – absorption peak and 585 nm – shoulder peak) and a red polymer phase (~560 nm – absorption peak and in region from 480 nm to 580 nm). Meanwhile, the bluish-green polyPCDA phase (~671 nm – absorption peak) is completely absent. The dominant is the blue phase polymer found in EBT 3 film. This is the main reason that cause the color of EBT 3 film change to blue after the exposure (Callens et al. 2015).

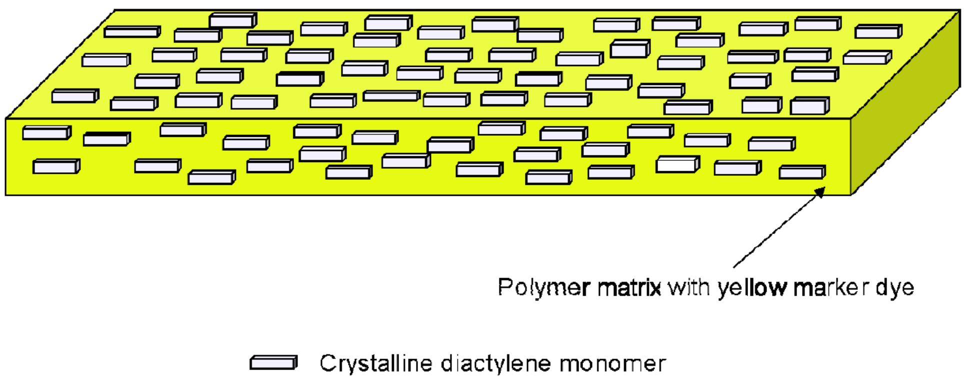

Figure 2.4 Active layer of the film containing yellow marker dye and crystalline diactylene monomer (Lewis 2014)

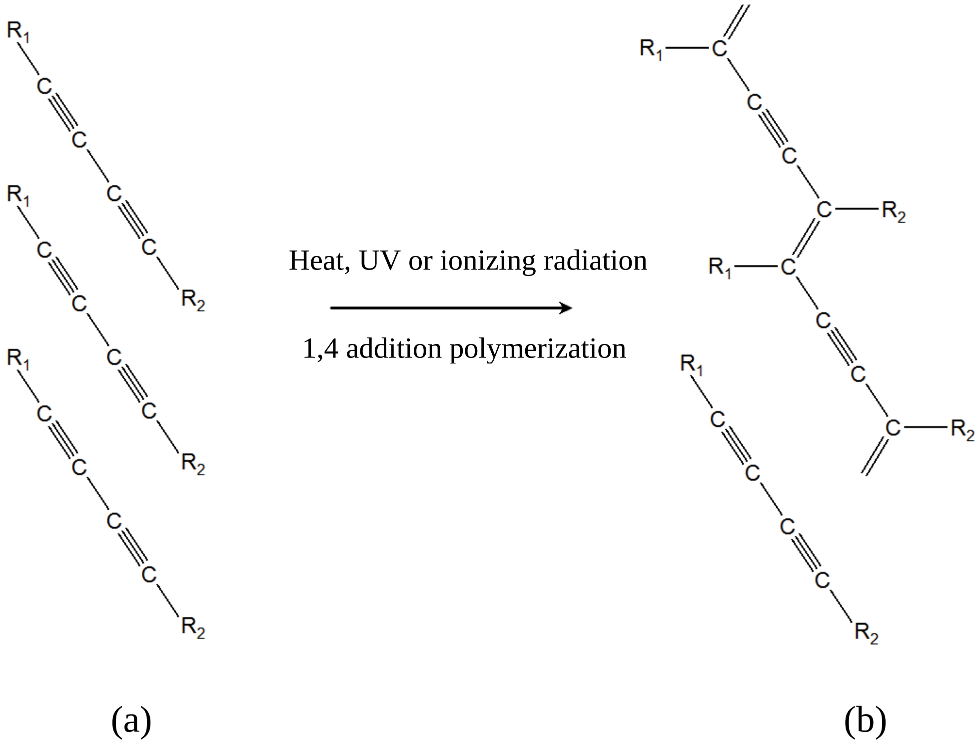

Figure 2.5 a) colourless monomer b) colored polymer (Williams & Metcalfe 2011)

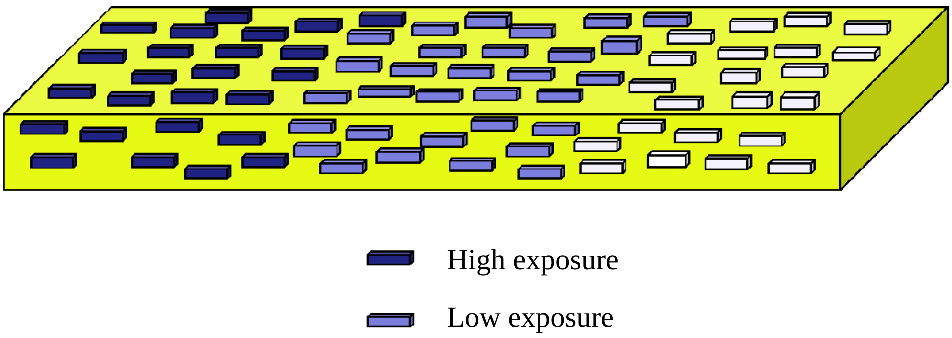

Figure 2.6 The different color of the monomer to differentiate the darkness color of the film before and after expose with low and high exposure (Lewis 2014).

2.3.2 Review on the Application of EBT3 Film

Several studies are made on Gafchromic EBT 3 film. The EBT 3 film is used for in-vitro sun protection factor (SPF) test based on UV dosage cumulate response. The purpose is to check the actual SPF label on the commercial sunscreen lotion is tally with the SPF obtain using EBT 3 film method and spectrophotometer method. The result shows that EBT 3 film method is more accurate than UV spectrophotometer method with 3M tape and Poly (methyl methacrylate) (PMMA) plate as substrates based on the in-vitro SPF results tested from 17 commercial products (i.e, 2 sunscreen standards and 15 commercial products, including sunscreen lotions, BB creams, foundations and sprays with organic and/or inorganic UV filters). This study concludes that EBT 3 film method is more accurate, cost effective, reproducible, and not require UV spectrophotometer compare to current test methods (Qu et al. n.d.).

The method of ultraviolet radiation with diffuser tips using radiochromic film can avoid potentially dangerous exposure conditions. The advantages of film analysis including quick (minimal processing) and inexpensive method that generates high exposure sensitivity and much simpler high-resolution results without the need for a complex and expensive goniometer setup and detection system. This film is positioned in a cylinder around the diffuser. The light is emitted from the diffuser onto the film and the film change color relative to the exposure amount as shown in Figure 2.3 (Welch, Spotnitz, et al. 2017).

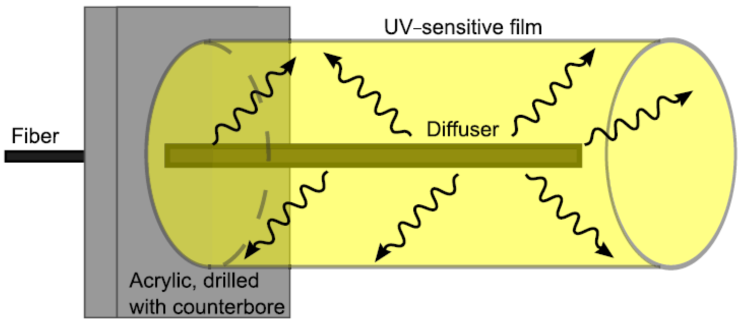

Figure 2.7: The optical diffuser within the cylinder of UV-sensitive film. The diffuser emits photons in all directions which change color of the film (Welch, Spotnitz, et al. 2017)

There are several studies about the saturation at higher dose level for Gafchromic EBT and EBT 3 films. The study on EBT film reported by (Lynch et al. 2006), stated that optical density (OD) increase with rising temperature during scanning with charge-coupled device (CCD) flatbed scanner, whereas (Rink et al. 2008) found the opposite, showing a decrease in OD with increasing temperature. (Rink et al. 2008) evaluated that the increase in OD based solely on the newly formed polymers. (Rink et al. 2008) also suggested that the observed negative change in net OD was unlikely to be due to a decrease in the intrinsic sensitivity or polymerization kinetics of the active component and was probably caused by temperature induced changes in absorption or reflection coefficients of the various layers in the film. However, the recent study made by (Callens et al. 2017), investigate the darkening of Gafchromic EBT 3 films in relation to dose by joining the optical properties of the polydiacetylene polymer phases and a modified version of the single-hit model. The comparison also made between flatbed scanning and UV-vis absorption spectroscopy in quantification of the film darkness. The results prove that the increasing polymer concentration with radiation dose is successfully described by the modified single-hit model using a log-normal distribution for the length of the stick-like monomer microcrystals. (Callens et al. 2017) clarify that 635 nm of UV-vis spectroscopy can accurately quantify the absorption properties of the film for dose levels less than 10 Gy but over 10 Gy, the absorption spectrum saturates due to the small amount of light transmitted through the film and limited sensitivity of the spectrometer. (Callens et al. 2017) found that the dose in relation to the polymer content, concluded from the UV-vis absorption spectrum which is more sensitive to changes in dose, varies from flatbed scanning method which is less sensitive.

The uncertainty of the radiochromic film has also been investigated. (Richley et al. 2010) found that although EBT 2 film has the addition of yellow marker dye, this film still sensitive to ambient light, but the film's sensitivity to light can be reduced by keeping films in light-tight packets. There is no effect when the repeated scanning is done on the film. The film continues to darken following irradiation and recommend performing calibration at the time of the exposure to reduce uncertainty. The purpose of yellow dye is for improving the film homogeneity. (Richley et al. 2010) identify that the source that cause highest uncertainty is from the non-uniformity of the scanner which is thought due to the light scattering effect, appearing from the structure and thickness of EBT 2 film. The uncertainties in dose is also found to be greater in reflection mode than in transmission mode as in Figure . (Richley et al. 2010) also clarify that these uncertainties appear from the scanner, film and system, thus, important to understand and characterize every aspect of the film, scanner and software system before used (Richley et al. 2010). Nevertheless, (Park et al. 2012) stated that continuous scanning orientation and minimal exposure to room light can reduce uncertainty in the measured dose (23 ± 3%) for the transmission mode scanning due to this scanning has high dependence on film orientation scanning and change in OD from room light exposure. But, based on (Park et al. 2012), the reflection scanning mode has quite good stability with respect to room light and film orientation on a scanner, although the large uncertainty in measured dose. Still, the transmission scanning mode is recommended for dosimetry as it provides better uncertainty results, but, (Park et al. 2012) suggest that reflection scanning mode can also bring a potential advantage for film dosimetry in radiotherapy.

Besides that, the uncertainty analysis of the dose also performed by (León Marroquin et al. 2016) to study intrinsic characteristics of film dosimetry which were found related to the relative orientation of the EBT 3 film, the uniformity of response of the scanner and the fitting procedure. The results for the analysis of the response of net OD EBT 3 film and the fitting of the experimental data to a potential function shows uncertainty of 2.6% (red), 4.3% (green) and 4.1% (blue) channels. The results also show less uncertainty when the films are scanned in portrait mode compare in landscape mode. When placing film around the center of the bed of scanner, the uncertainty is 2% (red), 3% (green) and 4.5% (blue). The overall uncertainty in dose is less than 1% for the uniformity and reproducibility EBT 3 film and reproducibility of response of scanner. The total dose uncertainty was 3.2% (red channel), 4.9% (green channel) and 5.2% (blue channel). They conclude that radiochromic films can be used in a wide range of applications in 0-120 Gy considering their uncertainties as a function of dose (León Marroquin et al. 2016).

EBT 2 and EBT 3 film has negligible differences on post-irradiation darkening, film orientation, film uniformity and energy dependency. The EBT 3 film shows a minimal improvement in face-up or down dependence and the matte film surface of EBT 3 film can eliminate completely the Newton rings (Dreindl et al. 2014). (Dreindl et al. 2014) also evaluate the dosimetric behavior of EBT 2 and EBT 3 films over a period greater than 6 months and found that there is a shift of the calibration curve for both EBT 2 and EBT 3 films due to changes in the dynamic response of the active component. (Dreindl et al. 2014) concluded that the new EBT 3 film provide comparable results with EBT 2 film and the general advantages of radiochromic film dosimeters are high film homogeneity, low energy dependence and less dependence on face-up or down.