การศึกษาคุณสมบัติของฟิล์มชนิด Gafchromic^{TM} EBT เพื่อใช้ในการประกันคุณภาพของลำโฟตอนพลังงานสูง

นายปรเมศวร์ วงศ์จอม

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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ปีการศึกษา 2552

THE CHARACTERISTICS OF GAFCHROMIC™ EBT FILM FOR DOSIMETRIC VERIFICATION FOR HIGH ENERGY PHOTON BEAMS

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Medical Imaging
Department of Radiology
Faculty of Medicine
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Field of Study	Medical Imaging
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ปรเมศวร์ วงศ์จอม: การศึกษาคุณสมบัติของฟิล์มชนิด Gafchromic™ EBT เพื่อใช้ในการประกันคุณภาพของลำโฟตอนพลังงานสูง. (THE CHARACTERISTICS OF GAFCHROMIC™ EBT FILM FOR DOSIMETRIC VERIFICATION FOR HIGH ENERGY PHOTON BEAMS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ศิวลี สุริยาปี, 58 หน้า.

การศึกษานี้มีวัตถุประสงค์เพื่อหาคุณลักษณะของฟิล์มชนิด Gafchromic รุ่น EBT สำหรับลำโฟตอนพลังงานสูงและเพื่อที่จะตรวจสอบการกระจายปริมาณรังสีด้วยเทคนิคที่ซับซ้อน โดยจะทำการศึกษาหาคุณลักษณะของเครื่อง Scanner ยี่ห้อ Epson Perfection V700 และ ฟิล์มชนิด Gafchromic รุ่น EBT การศึกษาคุณลักษณะของเครื่อง Scanner ประกอบด้วย การตอบสนองของเครื่อง Scanner ความสามารถในการทำซ้ำ ความสามารถในการทำใหม่ และ การตอบสนองของช่องสัญญาณแสงสี สำหรับการศึกษาคุณลักษณะของฟิล์ม ประกอบด้วย เวลาของค่าความเข้มสีคงที่ Polarization effect ความสม่ำเสมอของค่าความเข้มสี ผลของขนาดของลำรังสี ผลของอัตราปริมาณรังสี และ Repeatability rate effect การวัดค่า Percentage depth Dose และ Beam profile เพื่อเปรียบเทียบกับผลที่ได้จากการวัดโดย Ionization chamber ขนาด 0.13 ลบ.ซม. การเปรียบเทียบการกระจายของปริมาณรังสีโดยใช้ Fluence Map ที่วัดได้จากฟิล์มกับการคำนวณการกระจายปริมาณรังสีด้วยเครื่องคอมพิวเตอร์ (Eclipse treatment planning) ด้วยแผนการรักษา 3 แผน คือ Nasopharynx cancer 2 แผนการรักษา และ brain tumor 1 แผนการรักษา

การศึกษาคุณลักษณะของเครื่อง Scanner พบว่า การตอบสนองของเครื่อง scanner โดยความสัมพันธ์ระหว่าง ค่าพิกเซล และ ค่าความเข้มสีมีลักษณะเป็นเส้นโค้งแบบ Polynomial ค่าความแปรปวนของความสามารถในการทำใหม่และการทำซ้ำ อยู่ภายใน 1.0% และ 1.1% ตามลำดับ ช่องสัญญาณแสงสีแดงให้ค่าการตอบสนองสูงที่สุด การศึกษาคุณลักษณะของฟิล์ม พบว่า เวลาของค่าความเข้มสีคงที่ ประมาณ 4 ชั่วโมงหลังจากการฉายรังสี โดยค่าความเข้มสีเพิ่มขึ้น 7% ผลกระทบของ Polarization จะเกิดมากที่สุดที่ 90° และ 270° เมื่อเปรียบเทียบกับมุม 0° องศา และปริมาณรังสีมากจะมีผลกระทบน้อยกว่าปริมาณรังสีน้อย โดยปริมาณรังสี 50 cGy มีผลกระทบเพิ่มขึ้นถึง 24% ความแปรปวนของค่าความสม่ำของความเข้มสีของฟิล์มมีค่ามากถึง 7% สำหรับการฉายรังสีด้วยปริมาณ 400 cGy การวัดรังสีด้วยฟิล์ม พบว่าไม่ขึ้นกับอัตราปริมาณรังสี และ ผลของ Repeatability rate ความแตกต่างกันของการวัด Percentage depth dose ระหว่างฟิล์ม กับ Ionization chamber (CC13) พบว่า มีค่าความแตกต่างกัน 3.11% สำหรับขนาดของลำรังสี 2×2 ตร.ซม. ที่ความลึก 5 เซนติเมตร ค่าการเบี่ยงเบนของ Beam profile ระหว่างฟิล์ม กับ Ionization Chamber (CC13) พบว่า เกิดขึ้นที่บริเวณ Off-axis และบริเวณที่มีการเปลี่ยนแปลงปริมาณรังสีสูง สำหรับการเปรียบเทียบการกระจายของปริมาณรังสีโดยใช้ Fluence Map และใช้เกณฑ์ของค่าความแตกต่างของปริมาณรังสี 3% และ ความแตกต่างของระยะทาง 3% พบว่า 2 แผนการรักษาแสดงค่าเปอร์เซ็นต์ผ่านเกิน 90% แต่อีก 1 แผนการรักษาแสดงค่าเปอร์เซ็นต์ผ่านน้อยกว่า 90%

การศึกษาคุณลักษณะของเครื่อง Scanner จำเป็นที่จะปฏิบัติเป็นอันดับแรกก่อนที่จะทำการศึกษาคุณลักษณะของฟิล์ม รุ่น EBT ซึ่งประกอบด้วย เวลาของค่าความเข้มสีคงที่ Polarization effect และ ความสม่ำเสมอความเข้มสีของฟิล์ม เนื่องจากควรเลือกช่วงเวลาที่เหมาะสมที่สุดในการนำฟิล์มมาอ่านค่าความเข้มสี และ ทิศทางของการ Scan โดยหลีกเลี่ยงผลกระทบของค่า Polarization ให้น้อยที่สุด สำหรับค่าความสม่ำเสมอความเข้มสีของฟิล์ม รุ่น EBT และเครื่อง Scanner รุ่น Epson Perfection V700 จำเป็นต้องทำการแก้ค่าความแปรปรวน ของสัญญาณก่อน เนื่องจากจะส่งผลกระทบมากต่อการตรวจสอบการกระจายของปริมาณรังสีที่วัดได้

จากการศึกษาคุณลักษณะของฟิล์มชนิด Gafchromic รุ่น EBT พบว่า สามารถใช้เป็นเครื่องมือใหม่ สำหรับลำโฟตอนพลังงานสูงเพื่อที่จะตรวจสอบการกระจายปริมาณรังสีด้วยเทคนิคที่ซับซ้อนได้

ภาควิชา รังสีวิทยา ลายมือชื่อนิสิต ปรเมศวร์ วงศ์จอม

สาขาวิชา ฉายาเวชศาสตร์ ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ศิวลี สุริยาปี

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#5174788630: MAJOR MEDICAL IMAGING

KEYWORDS: GAFCHROMIC^{TM} EBT FILM / RADIOCHROMIC FILM/ INTENSITY MODULATION RADIOTHERAPY (IMRT) / DOSIMETRIC VERIFICATION.

PORAMED WONGJOM: THE CHARACTERISTICS OF GAFCROMIC^{TM} EBT FILM FOR DOSIMETRIC VERIFICATION FOR HIGH ENERGY PHOTON BEAMS. THESIS ADVISOR: ASSOC.PROF. SIVALEE SURIYAPEE, 58 pp.

The objectives of this research are to study the characteristics of Gafchromic^{TM} EBT film for 6 MV x-ray photon beams and to verify isodose distribution of advanced radiation treatment techniques.

The characteristics of Epson perfection V700 flat-bed color CCD were studied for the response, repeatability, reproducibility and color band of scanner. The characteristics of Gafchromic^{TM} EBT film were investigated for speed of film development, polarization, uniformity, field size, dose rate and repeatability rate effect. The percentage depth dose and beam profile were measured and compared with the data from ionization chamber. The comparisons of fluence map measured by film and calculated by Eclipse treatment planning were observed for two nasopharynx caner and one brain tumor.

The response of Epson perfection V700 flat-bed color CCD in term of pixel value and net optical density showed the polynomial curve. The variations of scanner reproducibility and repeatability were within 1.0% and 1.1%, respectively. The Gafchromic^{TM} EBT film was best evaluated in the red channel of the Epson perfection V700 scanner. The optical density growths with time seem to stabilize after 4 hours and increasing up to ±7 %. The effect of EBT film polarization at 90^0 and 270^0, with 50 cGy delivered dose was up to 24% difference when compared with orientation at 0^0. The variation of EBT film uniformity was ±7 % at 400 cGy. The film responses did not depend on the dose rate and repeatability rate. The difference of percentage depth dose between EBT film and CC13 ionization chamber was 3.11% for 2×2 cm^2 field size at 5 cm depth. The deviation of beam profile between EBT film and CC13 ionization chamber was presented at region of off-axis and high dose gradient. The fluence map measured by Gafchromic^{TM} EBT and calculated by Eclipse planning system of two nasopharynx cancer and one brain tumor were compared with the criterion of 3% dose difference and 3 mm distance to agreement. The two plans showed over 90% passed but one plan was below 90%.

The characteristics of scanner should be studied before examined the characteristics of Gafchromic^{TM} EBT film. The characteristics of film such as speed of film development, polarization effect and uniformity were very important because of the stability time of net optical density and the direction of non-polarization effect should be selected. The uniformity of film affected to dose distribution verification, it should be corrected before scanning the film. Then, the Gafchromic^{TM} EBT films can be implemented to verify isodose distribution of advanced radiation treatment techniques.

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Field of Study: Medical Imaging Advisor's Signature Sivalee Suriyapee

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LIST OF ABBREVIATIONS

Abbreviation	**Terms**
μm	Micrometer
2D	Two Dimensions
3D	Three Dimensions
4D	Four Dimensions
AAPM	American Association of Physicists in Medicine
ADCLs	Accredited Dosimetry Calibration Laboratories
BNC	Bayonet Neill-Concelman
CA	Cancer
CC13	Compact Chambers 13 (Cavity volume size of 0.13 cm^3)
CCD	Charge Coupled Device
cGMP	Current Good Manufacturing Practices
cGy	Centi-Gray
cGy/min	Centi-Gray per Minute
cGy/MU	Centi-Gray per Monitor Unit
cm	Centimeter
cm^2	Centimeter Square
cm^3	Cubic Centimeter Square
CT	Computed Tomography
DICOM-RT	The Digital Imaging and Communications in Medicine-Radiotherapy
D_{max}	Maximum Dose
E	Electromagnetic Field
Gafchromic ^{TM} EBT film	Film Type Using in External Beam Therapy
EDR2 film	Film Type of Extended Dose Range 2
FDA	Food and Drug Administration
Gy/C	Gray per Coulomb

Abbreviation	Terms
HD	High Dose
HS	High Sensitive
I	Intensity
IEC	International Electrotechnical Commission
IMRT	Intensity-Modulated Radiation Therapy
kV	Kilo-Voltage
kVp	Kilo Peak Voltage
MeV	Mega-Electron Voltage
MLC	Multileaf Collimator
mm	Millimeter
MR	Magnetic Resonance
MUs	Monitor Unit
MV	Mega-Voltage
netOD	Net Optical Density
OD	Optical Density
PDD	Percentage Depth Dose
PTV	Planning Target Volume
QA	Quality Assurance
RCF	Radiochromic Films
ROI	Region of Interest
SSD	Source Skin Distance
TLDs	Thermoluminescent Dosimeters
TNC	Threaded Neill-Concelman)
USA	United States of America

CHAPTER I

INTRODUCTION

1.1 Background and Rationale

In the present day, technologies of radiation treatment techniques have been developed to treat patient efficiency. Therefore, the old techniques of radiation treatment will be replaced with new irradiation advanced technique such as Intensity Modulated Radiotherapy (IMRT), 4D respiratory gating, dynamic arc and volumetric arc etc. With increasing complexity of advance techniques delivery modalities, there is a growing demand for validating delivered dose distributions in multiple dimensions [1]. Therefore, the dosimeter for measuring dose distribution must be accurate and efficient for the good benefit of treatment results.

The IMRT technique requires steep dose gradient to achieve the target conformal avoidance of the critical structures presented in the treatment volume. High dose gradient is the result of varying intensity of the individual beam. Using a number of small beams, potentially with different monitor units (MUs), is one of the ways to get the required modulation in the field. This complex nature and delivery pattern of complex irradiation techniques make the requirement to check the consistency between the calculation and delivered dose. Although the absolute point dose can be measured with good accuracy using an ionization chamber, the large volume of the chamber affects the dose measurement at steep dose gradient regions. Diode detectors with small sensitive volume having high sensitivity are comparable to ionization chamber; however, their directional dependency marks them inefficient for dose measurements [2]. Thermoluminescent dosimeters (TLDs) offer a better spatial resolution compared to the ionization chambers and diode detectors; however, they require laborious processing of large number of detectors place in a well designed phantom to measure the dose distribution of new irradiation technique. Moreover, it is impractical to map the complex irradiation techniques dose distributions using a collection of individual detectors.

Two-dimensional (2D) high-resolution dose distribution measurements can be performed using silver halide radiographic films. However, radiographic film sensitivity is known to be a function of photon beam energy and orientation of exposure. The film response to the megavoltage beam seems to increase with the depth and filed size at which measurement were taken, due to increase population of low-energy Compton scattered photon with increase depth and field size. The ratio of mass energy absorption of film to water also rapidly increase as the energy decrease (less than approximately 400 keV) [3] , due to the dominant photoelectric interaction of the low-energy photons with high atomic number material, silver, present in the radiographic film. The problem associated with radiographic film dosimetry is that, in addition to their spectral response, the dose response is strongly affected by processing condition, such as processor equipment type, chemicals, processing time, and temperature. Significant artifacts produce by the readout systems, such as densitometer and scanner, also yield considerable errors in dose distribution measurements.

Self-developing radiochromic films (RCF) have solved some of the problem associated with the silver halide radiographic film. RCF is a thin transparent film that is colorless before irradiation and turns to a deep blue, red, or green color upon irradiation [4]. No chemical, physical, or thermal processing is required to bring the image on the film; the color formation is a result of polymerization process induced by ionizing radiation in the sensitive layer of the film. The density of the color formed is directly proportional to the amount of dose deposited. The optical density (OD) of irradiated film can be measured using optical measuring systems such as spectrophotometers densitometers, or film scanner. Hence, multidimensional dose distribution measurements can be obtained by converting measured OD into absolute or relative dose [5].

Various types or radiochromic films (HD 810, DM 1260, DM 55, NMD 55, and HS), referred as Gafchromic^{TM} films, are commercially available. Each type principally differs from the other by its sensitometric response to dose and its dependence on environmental parameter [6]. Their sensitivity to daily clinical dose range and unacceptable variation in spatial uniformity hinder the use of Gafchromic films for dose distribution verification of new irradiation techniques. Recently, a new type of Gafchromic^{TM} film referred as Gafchromic External Therapy (EBT) was introduced. As quoted by manufacture, EBT film can be use in the dose range of 0.01 to 8 Gy, which falls within the limit of daily clinical dose range, with better uniformity compared to previous models of Gafchromic films.

This study aims to investigate the characteristics of Gafchromic^{TM} EBT film for dosimetric verification of 6MV photon beams. The measured isodose distribution for IMRT plan from Gafchromic^{TM} EBT film was compared to the data from treatment planning which the gamma value was used for evaluation.

1.2 Research objectives

1.2.1 To study the dosimetric characteristics of Gafchromic EBT film for high energy photon beams.

1.2.2 To verify isodose distribution of advanced radiation treatment techniques.

CHAPTER II

REVIEW OF RELATED LITERATURE

2.1 Theories

2.1.1 Historical background of radiochromic dosimeters [4]

Radiochromic effects involve the direct coloration of a material by the absorption of energetic radiation, without requiring latent chemical, optical, or thermal development or amplification. The radiochromic process, involves the production of immediate permanent colored images of a radiation exposure pattern in a solid, with or without “fixing” of the sensor medium against further change.

2.1.2 Configuration and structure of Gafchromic^{TM} EBT film [7]

Gafchromic^{TM} EBT is made by laminating two coatings each having an active layer approximately 17 µm thick and a surface layer approximately 3 µm thick. The coatings are applied to clear, transparent 3.8 mil (~97 µm) polyester. The product is formed by laminating the two pieces of coated film by a proprietary technique requiring no intermediate adhesive layer. The EBT laminate is identified by its batch number. At all steps of the manufacturing process the intermediates and components are identified by their batch numbers and the manufacturing process is done in compliance with cGMP as required for radiographic x-ray film FDA Class 1 medical device. Figure 2.1 shows the configuration of Gafchromic^{TM} EBT film. Table 2.1 contains details of the atomic compositions of Gafchromic^{TM} EBT dosimetry film. The effective atomic number has been calculated according to McCullough and Holmes, *Med. Phys.*, 12:237-242, 1985. The Z_{eff} is 6.98. This value is closer to the Z_{eff} of water (7.3) than the value for Gafchromic^{TM} MD-55 (~6.5).

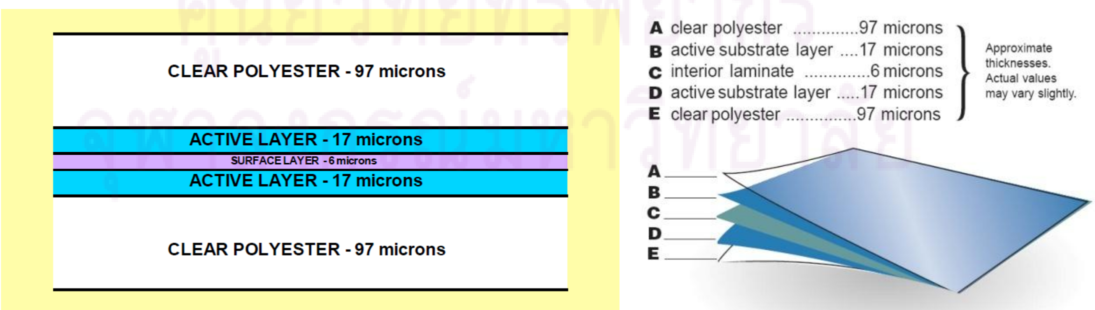


Figure 2.1 Configuration of Gafchromic^{TM} EBT dosimetry film.

Table 2.1 Atomic composition and effective atomic number of Gafchromic^{TM} EBT dosimetry film**.**

Atomic composition						$Z_{eff} = \left[\sum\_i (Z_i) a\right]^{1/a}$
C	**H**	**O**	**N**	**Li**	**Cl**	
42.3%	39.7%	16.2%	1.1%	0.3%	0.3%	6.98

2.1.3 Gafchromic^{TM} EBT dosimetry film characteristics [7]

This high sensitivity radiochromic film has been designed for the measurement of absorbed dose of high-energy photons used in IMRT. The film was designed for using in the 1 cGy to 800 cGy dose range. The response to photons has been found to be energy-independent in the MeV range and measurements at energies down to about 30 keV reveal that the sensitivity changes by less than 10%.

2.1.3.1 Measurement

Gafchromic^{TM} EBT dosimetry film can be measured with transmission densitometers, film scanners or spectrophotometers. When the active component is exposed to radiation, it reacts to form a blue colored polymer with absorption maxima at about 636 nm and 585 nm. As shown in Figure 2.2 the absorbance spectrum of EBT film is similar to that of Gafchromic^{TM} HS except that the peaks shifted about 35 nm to shorter wavelength. Peak absorption of Gafchromic^{TM} EBT is at 636 nm. Consequently the response of this dosimetry film will be enhanced by measurement with red light.

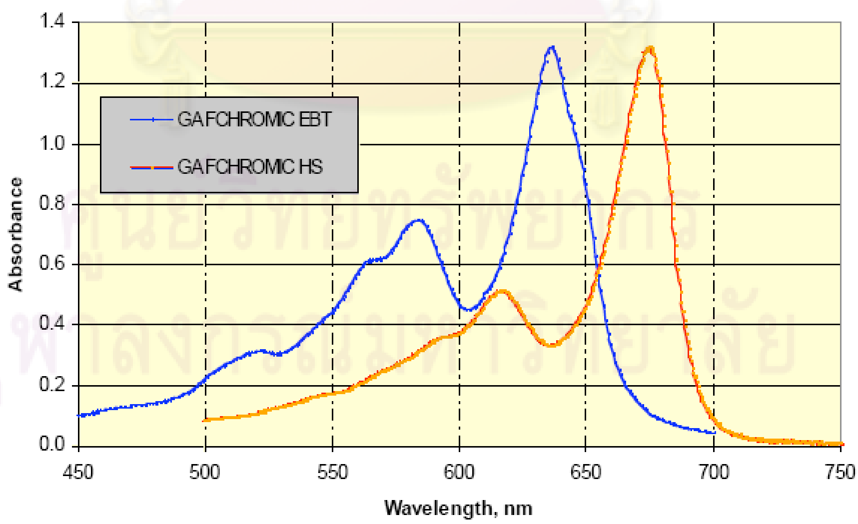


Figure 2.2 Absorption spectra of Gafchromic^{TM} HS and EBT dosimetry films**.**

2.1.4 Dose resolution [7]

A film scanner measuring a transparency determines the amount of light transmitted by the film. A scanner with 16 bit resolution assesses the transmission on a scale from 0 (no transmission) to 65535 (high transmission). The intensity of the transmitted light is reported as the pixel value (PV). The dose resolution, Δd, of a film and film-scanner system depends upon the slope of the dose response curve (PV vs. dose) and the standard deviation of a measurement $\sigma_{PV,d}$. This is depicted in Figure 2.3. Assuming that the variability of the measurement of a single pixel has a normal distribution and beginning with the criterion that we would like to know the dose of a single pixel to a confidence of 90%, we can evaluate the dose resolution at a dose d by calculating Δd for pixel values that range from PV-1.65$\sigma_{PV,d}$ to PV+1.65 $\sigma_{PV,d}$.

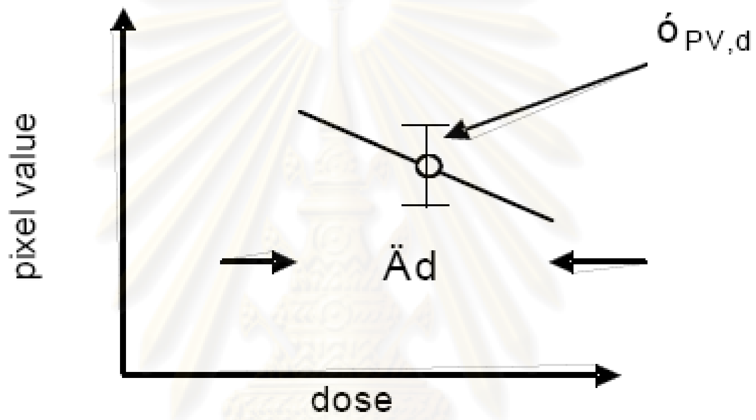


Figure 2.3 Slope of the dose response curve.

2.1.5 Energy dependence [7]

Gafchromic MD-55 and HS dosimetry films contain only low Z elements - C, H, N and O – and these films show a lower dose response to keV photons than MeV photons. At about 50 keV the response is about 20% less than at 6 MeV. The presence of a minor amount of the moderate Z element chlorine in the atomic composition of EBT film suggests that photoelectric absorption of keV photons in this film will be boosted, particularly below 50 keV. Consequently EBT film may exhibit less energy dependency than the earlier radiochromic films. The energy dependence was assessed by measuring the dose-density response of the film with cobalt-60 radiation and with several different quality kilovoltage x-ray beams. The results shown in Figure 2.4a indicate that under these exposure conditions, at least, the EBT film has a very low energy dependency, showing not more than a 5% difference between MeV and keV photons.

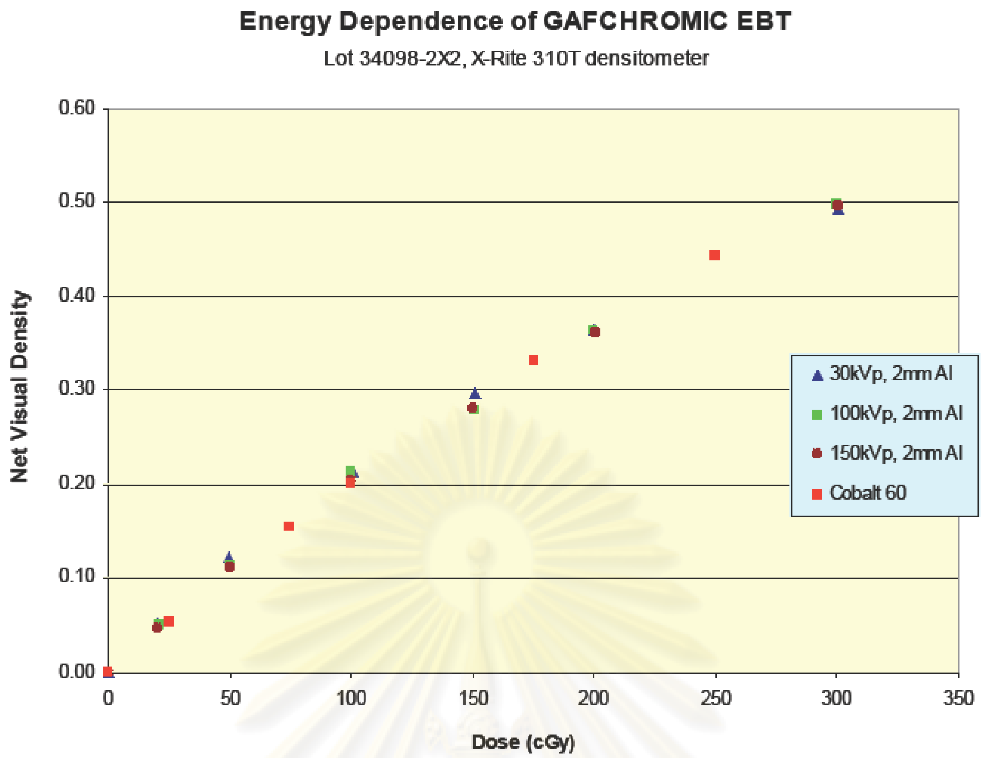


Figure 2.4a Energy dependence of Gafchromic^{TM} EBT dosimetry film.

Other measurements of EBT film with photons and electrons in the megavoltage region were reported at AAPM in 2004 by Jameson Baker, et al. Their data, Figure 2.4b, shows that the film has the same response to electrons at 6 MV and 15 MV and to 6 MeV, 12 MeV and 20 MeV photons.

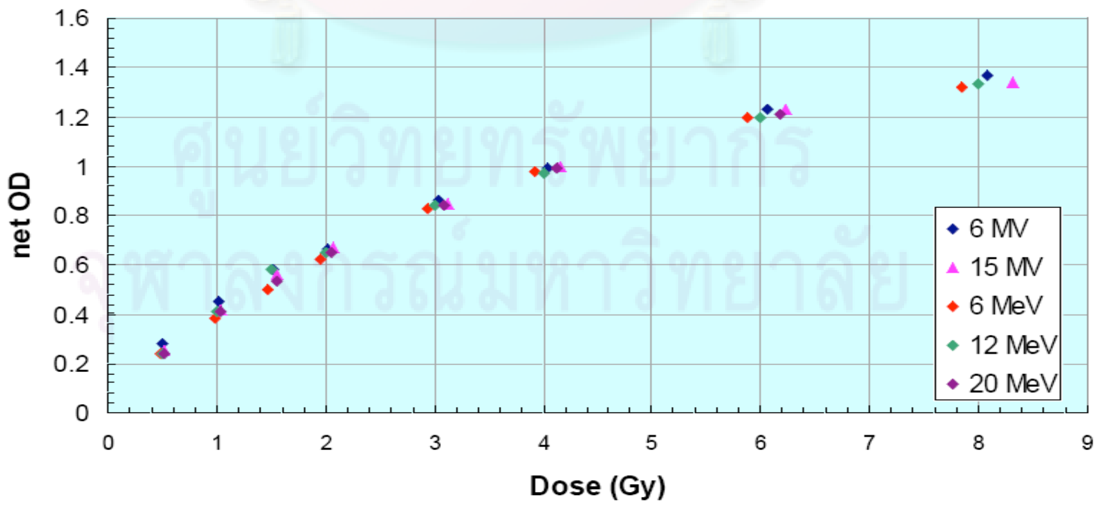


Figure 2.4b Energy dependence of Gafchromic^{TM} EBT dosimetry film.

2.1.6 Dose fractionation [7]

The effect of dose fractionation upon the exposure of Gafchromic^{TM} EBT film was assessed by exposing film samples 5 Gy of 150 kVp x-rays with 2 mm Al filtration. Three film samples were exposed to the 5 Gy in a single fraction in about 2 minutes. A further three samples were exposed to 5 Gy given in 1 Gy fractions at 30 minute intervals. The change in visual density of all samples was measured 24 hours later. Table 2.2 indicates that the responses of the films exposed to a single fraction are indistinguishable from the response of the films given fractionated exposure.

Table 2.2 Response of Gafchromic^{TM} EBT dosimetry film to fractionated exposure.

Exposure	Net visual density change (average of 9 measurements)
5Gy in a single fraction	0.681 ± 0.015
5Gy in 1Gy fractions at 30min. intervals	0.677 ± 0.009

2.1.7 Dose rate dependence [7]

In a private communication, Alexandra Rink, et al report data showing that if time is allowed for the radiation induced polymerization to go to completion (>2 hours), the EBT film does not exhibit a dose rate dependence.

2.1.8 Film uniformity [7]

Assuming that the noise contributors-scanner, film and film exposure are acting at random, the components add in quadrature to produce the total noise. It assumes that the flat field exposure really is flat and is perfectly symmetrical, i.e. it will make no contribution to the difference images. In this case the noise in difference images will result from noise in the scanner and noise in the film, i.e. non-uniformity in the film response. Since scanner noise has been determined to contribute about 0.4% the film non-uniformity is estimated to be less than about 1.2%.

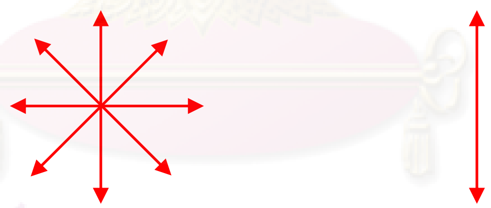
2.1.9 Polarization [8]

Figure 2.5 is demonstrated unpolarized light and polarize light. The most common technique for polarizing light is to send it though a material that passes only components of electric field vectors that are parallel to a characteristic direction of the material called the polarizing direction.

In figure 2.6, an unpolarized light beam is incident on the first polarizing sheets, called the polarizer, where the transmission axis is as indicated. The light that passes through this sheet is polarized vertically, and the transmitted electric field vector is E_0. A second polarizing sheet, called the analyzer, intercepts this beam with its transmission axis at an angle of θ to the axis of the polarizer. The component of E_0 that is perpendicular to the axis of the analyzer is completely absorbed, and the component parallel to that axis is $E_0 \cos\theta$. We know from equation (2-1) that the transmitted intensity varies as the square of the transmitted amplitude, and so we conclude that the intensity of the transmitted (polarized) light varies as

$$I = I_0 \cos^2\theta \qquad (2\text{-}1)$$

where I_0 is the intensity of the polarized wave incident on the analyzer. This expression, known as Malus's law, applies to any two polarizing materials whose transmission axes are at an angle of θ to each other. From this expression, note that the transmitted intensity is a maximum when the transmission axes are parallel (θ = 0 or 180^0) and zero (complete absorption by the analyzer) when the transmissions axes are perpendicular to each other.



(a) (b)

Figure 2.5 (a) an unpolarized light beam viewed along the direction of propagation. The time varying electric field vector can be in any direction in the plane of the page with equal probability. (b) a linearly polarized light beam with the time-varying electric filed vector in the vertical direction.

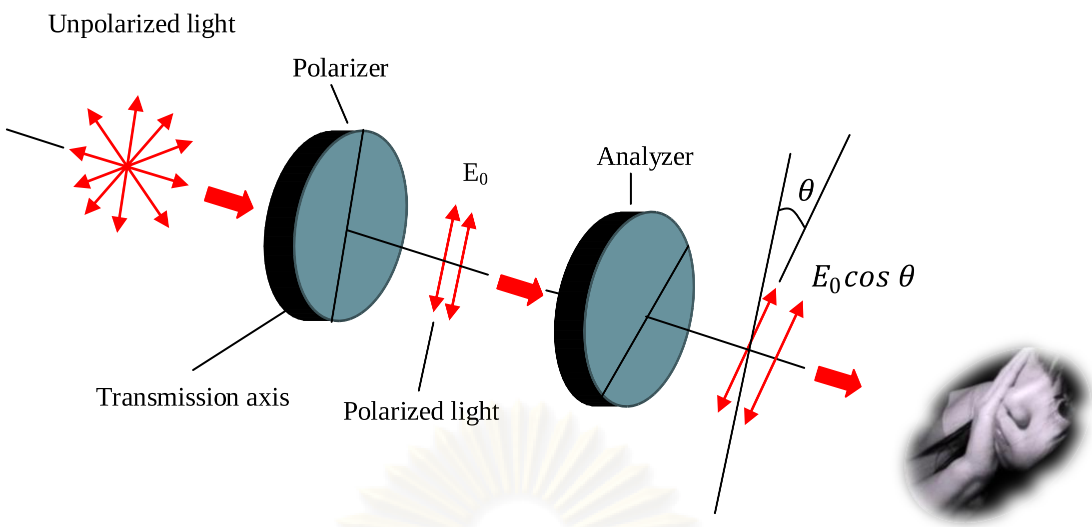


Figure 2.6 Two polarizing sheets whose transmission axes make an angle θ with each other. Only a fraction of the polarized light incident on the analyzer is transmitted through it.

2.1.10 Dose response relation [5]

For densitometers that do not read *OD* directly, the *net* $OD^i(D_j)$ and the $\sigma^i_{netOD}\ (OD\ )$ for a dose D_j can be calculated as follows:

$$netOD^i(D_j) = OD^i_{exp}(D_j) - OD^i_{unexp}(D_j)$$

$$= \log_{10}\frac{I^i_{unexp}(D_j) - I_{bckg}}{I^i_{exp}(D_j) - I_{bckg}} \qquad (2\text{-}2)$$

where $I^i_{une\,xp}(D_j)$ and $I^i_{exp}(D_j)$ are the readings for unexposed and exposed film piece for the *i*th film packet, respectively, while I_{bckg} is the zero-light transmitted intensity value, and using an error propagation expression that ignores cross correlations,

$$\sigma^i_{netOD}(D_i) = \frac{1}{\ln 10}\sqrt{\frac{(\sigma_{I^i_{unexp}}(D_j))^2 + (\sigma_{bckg})^2}{(I^i_{unexp}(D_j) - I_{bckg})^2} + \frac{(\sigma_{I^i_{exp}}(D_j))^2 + (\sigma_{bckg})^2}{(I^i_{exp}(D_j) - I_{bckg})^2}} \qquad (2\text{-}3)$$

All quantities in Eqs. (2-2) and (2-3) are calculated over the same ROI for every film piece in each film packet. The final *net OD* for a particular dose point (D_j) was determined as a weighted mean:

$$netOD\left(D_j\right) = \frac{\sum_{i=1}^{N}(net\,OD^i(D_j))/(\sigma_{netOD}^i\ (D_j))^2}{\sum_{i=1}^{N}(1/(\sigma_{netOD}^i\ (D_j))^2)} \qquad (2\text{-}4)$$

where the corresponding uncertainties were calculated as

$$(\sigma_{netOD}^i\ (D_j))^2 = \frac{1}{\sum_{i=1}^{N}(1/(\sigma_{net\ OD}^i\,(D_j))^2)} \qquad (2\text{-}5)$$

and the summation is over the *N* calibration packets of film samples. Delivered dose (*D*) versus measured *netOD* was fitted using the analytical form

$$D_{fit} = b \cdot netOD + c \cdot netOD^n \qquad (2\text{-}6)$$

following the approach outlined in our previous work.

2.1.11 Output factor [9]

The radiation output at $z_{\max}$, in cGy/MU for a linac and cGy/min for a cobalt unit, increases with an increase in collimator opening or field size. This increase in output can be measured at $z_{\max}$ of each field size. Alternatively, the increase in output can be measured at a fixed depth for each field size and the output at $z_{\max}$ determined by using the appropriate central axis PDD values. Regardless of which measurement technique is used, the increasing output is normalized to the radiation output of the calibration field size, typically a 10 × 10 cm^2 field.

2.1.12 Percentage depth dose [10]

The quantity *percentage* (or simply percent) *depth dose* may define as the quotient, expresses as the percentage, of the absorbed dose at any depth *d* to the absorbed dose at a fixed reference depth d_0, along the central axis of the beam (figure 2.7). Percentage depth dose (*P*) is thus

$$P = \frac{D_d}{D_{d_0}} \times 100 \qquad (2\text{-}7)$$

For orthovoltage (up to about 400 kVp) and lower-energy x-ray the reference depth is usually the surface (d_0=0). For high energies, the reference depth is take at the position of the *peak absorbed dose* (d_0=d_m).

In clinical practice, the peak absorbed dose on the central axis is sometimes called the *maximum dose*, the *dose maximum*, the *given dose*, or simply the D_{max}. Thus

$$D_{max} = \frac{D_d}{P} \times 100 \qquad (2\text{-}8)$$

A number of parameters affect the central axis depth dose distribution. These include beam quality or energy, depth, filed size, and shape, source to surface distance, and beam collimation. A discussion of these parameters will now be presented.

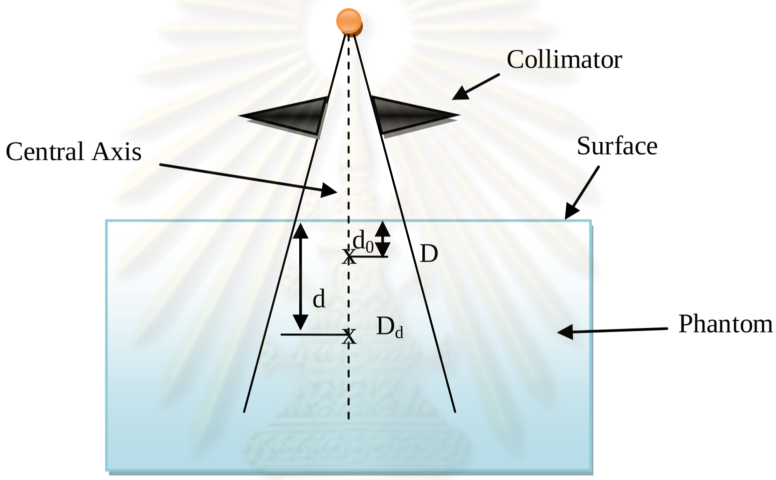


Figure 2.7 Percentage depth dose is (D_d/D_{do}) ×100, where d is any depth and d_0 is reference depth of maximum dose.

2.1.13 Isodose curve [11]

An isodose curve is a line of constant absorbed dose. The isodose curves are generally drawn at regular intervals of absorbed dose and are expressed as percentage of the dose at a normalization point. (i.e 80 percent, 70 percent etc.). A set of isodose curves is called isodose chart. These latter refer commonly to principal planes that are planes which contain the beam axis. Measurements of the isodose curves should be made in a water tank large enough to permit a full scatter condition to the point at which measurements is being made or in a tissue equivalent phantom. In Figure 2.8 isodose curves are shown for a normal incidence of the photon beam on a homogeneous phantom. The isodose curves could be measured by a ionization chamber, a solid state dosimeter, thermoluminescence dosimeters (TLD) and films. A precision carriage could be mounted within the water tank allowing the 3D placement of the detector at any position in the tank under the remote control of a computer.

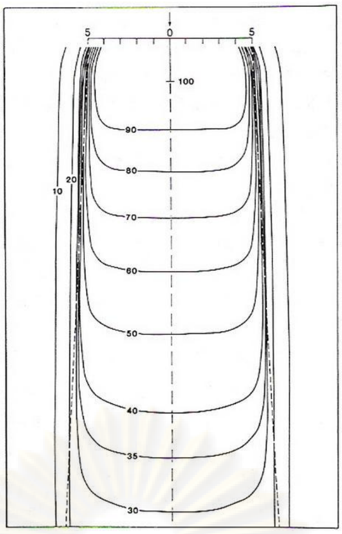


Figure 2.8 Isodose curves.

2.1.14 Intensity modulated radiotherapy [11]

Intensity modulated radiotherapy (IMRT) is a set of techniques of varying the intensity across the radiation field to deliver complex 3D dose distributions in external beam radiotherapy. It is found to be particularly useful in creating dose distributions with concavities, which are needed when the target is in close proximity to a dose limited critical organ.

Conventional radiotherapy uses a set of beams with fixed intensity profiles delivered in a cross fire effect to achieve a high dose to the target with maximal sparing of adjacent tissues. In IMRT the intensity profile of these beams is shaped such that the combined effect achieves the desired dose distribution. The added complexity generated by the extra degrees of freedom achievable with beam profile shaping means that the conventional manual, forward or interactive planning approach is generally not the best manner to plan the treatment and an automatic approach called inverse planning, or inverse optimization is used. This is a mathematical method of generating the treatment plan, in which a prescription is specified by the treatment planner in terms of doses to tumor and dose limits to critical structures. The computer then plans the beam distributions that produce a dose distribution that best matches the prescription.

Delivery of IMRT is most often achieved on a standard linac using a multileaf collimator, either as a set of static fields of differing shape from each beam direction or by scanning the leaves across the field during irradiation in the dynamic MLC technique. Other delivery systems for IMRT exist including intensity modulated arc therapy, tomotherapy and robotic radiotherapy.

2.1.15 Treatment planning technique [12]

Radiation treatment planning requires the calculation of a set of parameters for the delivery of a certain radiation dose to the patient. Ideally, radiation dose distribution should be designed to conform perfectly to the entire tumor volume while the completely avoiding surrounding normal tissues. Although achievement of the goal is practically impossible, a computer optimization can potentially simplify the tedious planning procedure and yield the best possible plans. Computer optimization becomes necessary for IMRT treatment planning because of the vast search space. The implementation of the general concept of inverse planning differs from system to system. The degree of optimality of the final solution is generally determined by (1) the form objective function; and (2) methods to search for the minimum (or maximum) of the objective functions.

2.1.16 Comparison between two dose distributions [13]

First, the geometric correction between the two distributions is established by using reference landmarks, ranging from pinprick marks in film to fiduciary markers containing CT- or MR-contrast that are placed on the phantom or patient. This geometric correction is mathematically achieved by a coordinate transformation to a coordinate system common to voxel grids. One of distribution will serve as the reference; the other one is denoted as evaluation distribution.

As both geometric and dosimetric accuracy are important in IMRT, Low et al., cleverly introduced the gamma (γ) index method. This evaluation method is base on a 4D distance concept: the three spatial (normalized) dimensions are supplemented with dosimetric (normalized) dimension. In each evaluation grid points, the 4D distance is computed to all reference grid point. The γ-value in that evaluation grid point is defined as the minimum of all these 4D distances. By respective normalization of the dimensions to the spatial tolerance criterion, e.g., 3 mm, and the dosimetric tolerance criterion, e.g., 4% difference between evaluated and reference dose, the evaluated voxels where $\gamma < 1$ can be considered to fall within tolerance and to be acceptable with regard to the reference dose distribution.

Conceptually, the gamma approach may be assessed in a difference way. Around any evaluation point, a fictive sphere is constructed with radius equal to the set spatial tolerance criterion. The γ-value will be lower than 1, i.e., the evaluation dose will be accepted, if a referenced position can be found within that sphere where the dose within a tolerance that decreases with distance (Figure 2.9a). The gamma tool inherently allows comparing flat dose as well as steep dose gradient regions.

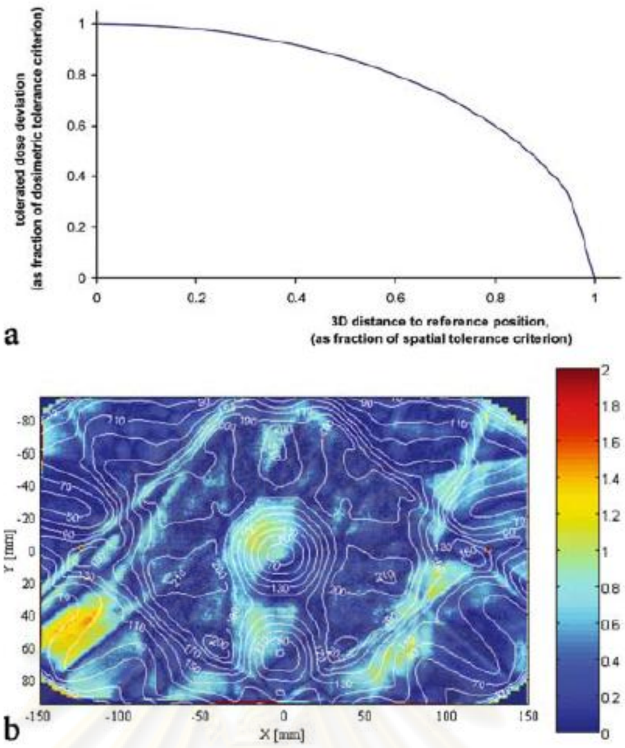


Figure 2.9 (**a**) The gamma (γ) concept allows to compare dose distributions in dosimetric and positional terms. Tolerated dose deviation as a function of 3D distance of the evaluation point to the reference position in order to keep $\gamma < 1$. (**b**) Example of film-measured γ-distribution in the transverse slice of a pelvic phantom that contained a fictive horse-shoe shaped PTV. A (3%, 3mm) tolerance criterion was used, the dosimetric criterion (3%) being expressed relative to the prescribed dose. The isodose lines of the computed dose distribution have been superposed. Apparently, the regions where $\gamma \geq 1$ (indicating > 3% dose difference and > 3mm spatial shift between computation and measurement) are situated in the lower-dose regions.

The gamma evaluation method is also applicable when one the distributions has a lower dimensionality. Gill et al. used the gamma method in a European QA multi-center study to compare 2D “composite film” (evaluate) dose to 3D computed (reference) dose. The gamma software routines were developed in the Matlab Version 6.1 (The MathWorks Inc., Natick, MA, USA) environment and the DICOM-RT and Image Processing toolboxes were used. Figure 2.9b displays the γ-distribution in the central transverse slice of the pelvic phantom used. By expressing dose difference relative to the prescribed dose, rather than relative to local dose, the analysis is more tolerance in low-dose regions.

A gamma analysis may also be useful to evaluate computed dose distributions against measured reference dose distribution for QA of treatment planning systems.

2.2 Review of related literatures

Menegotti L, et al. [14] reported for Radiochromic film dosimetry with flatbed scanners: a fast and accurate method for dose calibration and uniformity correction with single film exposure. The comparisons with a two-dimensional array of ionization chambers using a 18 × 18 cm^2 open field and an inverse pyramid dose pattern show an increment in the percentage of points which pass the gamma analysis (tolerance parameters of 3% and 3 mm), passing from 55% and 64% for the 1680Pro and V750 scanners, respectively, to 94% for both scanners for the 18 × 18 cm^2 open field, and from 76% and 75% to 91% for the inverse pyramid pattern. Application to an IMRT beam also shows better gamma index results, passing from 88% and 86% for the two scanners, respectively, to 94% for both. The number of points and dose range considered for correction and calibration appears to be appropriate for using IMRT verification. The method showed fast and corrects properly the non-uniformity and has been adopted for routine clinical IMRT dose verification.

Schneider F, et.al [15] investigated the optimization of the Gafchromic^{TM} EBT protocol for IMRT QA. The calibration curve shows a polynomial function of the fourth degree. The difference between the lowest and highest OD value of all these evaluated films, irradiated with different dose rates at a 6MV linac, is 0.46%. The energy dependent of relative point to point deviation ± standard deviation between 50 kV and 6 MeV is 4.77% ±1.33%. The color change of irradiated film was up to 2.5% in the first 5 days and another 2.0% in the next 25 days. The comparison of the film depth dose curve shows a relative pixel to pixel deviation ± standard deviation of 1.15% ± 0.76% and a maximum deviation of 3.1%.

Zeidan OA, et al. [1] reported the **c**haracterization and using of EBT radiochromic film for IMRT dose verification. They explored the dosimetric properties and implemented a new radiochromic film, type EBT, for IMRT dose verification. They found that Gafchromic EBT film was fully developed within 2 hour after exposed. The dose uniform of the film was shown to improve with higher dose exposures and can attain an overall uniformity level of ±1.5 % when exposed to uniform dose of 200 cGy. The new film showed a detectable OD response for doses as low as 25 cGy as resolved by the scanner used in their study. EBT film dose response with depth was shown to reproduce water scan relative depth doses to within ±4.0% and lateral relative dose profiles to within ±5%. The percent differences between measured and calculated doses for each IMRT plan inside a ROI of maximum uniform dose were within ±5%.

Van Battum LJ, et al [16] investigated accurate dosimetry with Gafchromic^{TM} EBT film of a 6 MV photon beam in water. They found the angular dependence on incident radiation beam which the measurement uncertainty is 0.25%. The measured net optical density values decrease in magnitude up to 1.0% with increasing angle of incident above an angle of about 70^0. The standard deviation per point of field size and depth dependence at 6 MV is 0.2%. The depth dose distributions of Gafchromic^{TM} EBT film data agree on average within ±1.0% with the ionization chamber data, with a maximum deviation of about ±3.0%. The maximum dose variation of beam profile between EBT film and ionization chamber is 4.6 cGy, while the average dose distribution is 1.8 cGy of 1.3%.

Rink A, et al. [17] studied for intra-irradiation changes in the signal of polymer-based dosimeter (Gafchromic^{TM} EBT) due to dose rate variations. Real-time measurements of ΔOD of Gafchromic^{TM} EBT films irradiated to doses in the 5 cGy to 1000 cGy range showed a small dose rate dependence when an eightfold difference in dose rate was introduced. Combining all ΔOD measurements for a given dose irrespective of dose rate used within the 16–520 cGy/min range introduced a dose rate dependent uncertainty of ∼1%. For all doses, the per cent standard deviation of the ΔOD values using all the dose rates within the tested range was <4.5%. Therefore, although varying dose rate by an order of magnitude has a statistically significant effect on the real-time ΔOD, the measurement can still be performed with an uncertainty of 4.5% of less, which can be satisfactory for many applications of the EBT film.

Sankar A, et al. [2] presented work deal with clinical use of commercially available self-developing Gafchromic EBT film for IMRT dose verification. Dose response curves were generated for the films using a VXR-16 film scanner. The results obtained with EBT films were compared with the results of Kodak EDR2 films. The EBT film had a linear response between the dose ranges of 0 to 600 cGy. There was up to 8.6% increase in the color density between 2-40 hours after irradiation. There was a considerable variation, up to 8.5 % in the film uniformity over it sensitive region. The EDR2 films showed consistent results with the calculated dose distributions, whereas the results obtained using EBT were inconsistent. The variation in the film uniformity limits the use of EBT film for conventional large-field IMRT verification. For IMRT of smaller field sizes (4.5×4.5 cm), the results obtained with EBT were comparable with results of EDR2 films.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Research design

This study is an observational descriptive study research.

3.2 Research design model

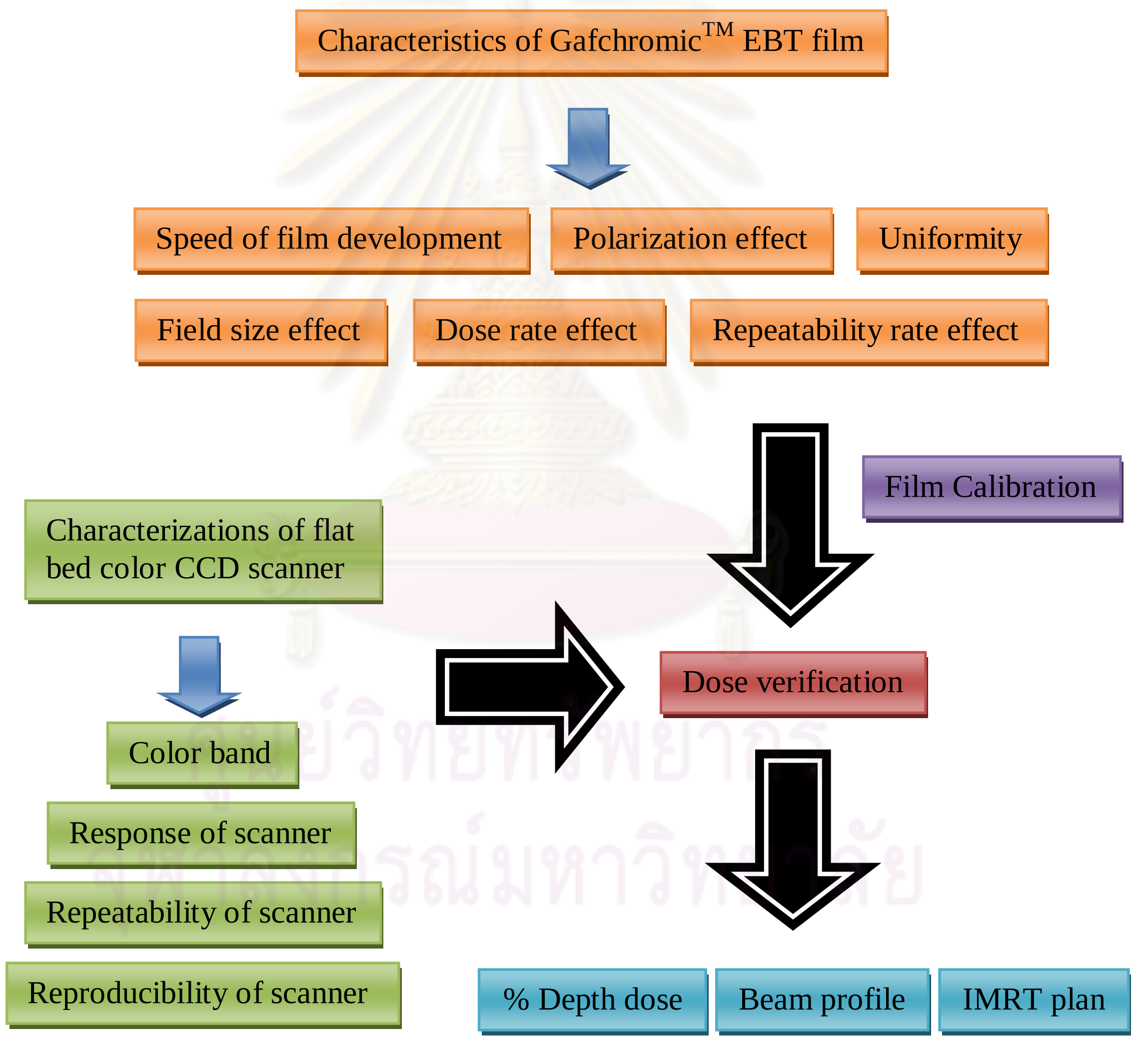


Figure 3.1 Research design model**.**

3.3 Conceptual frameworks

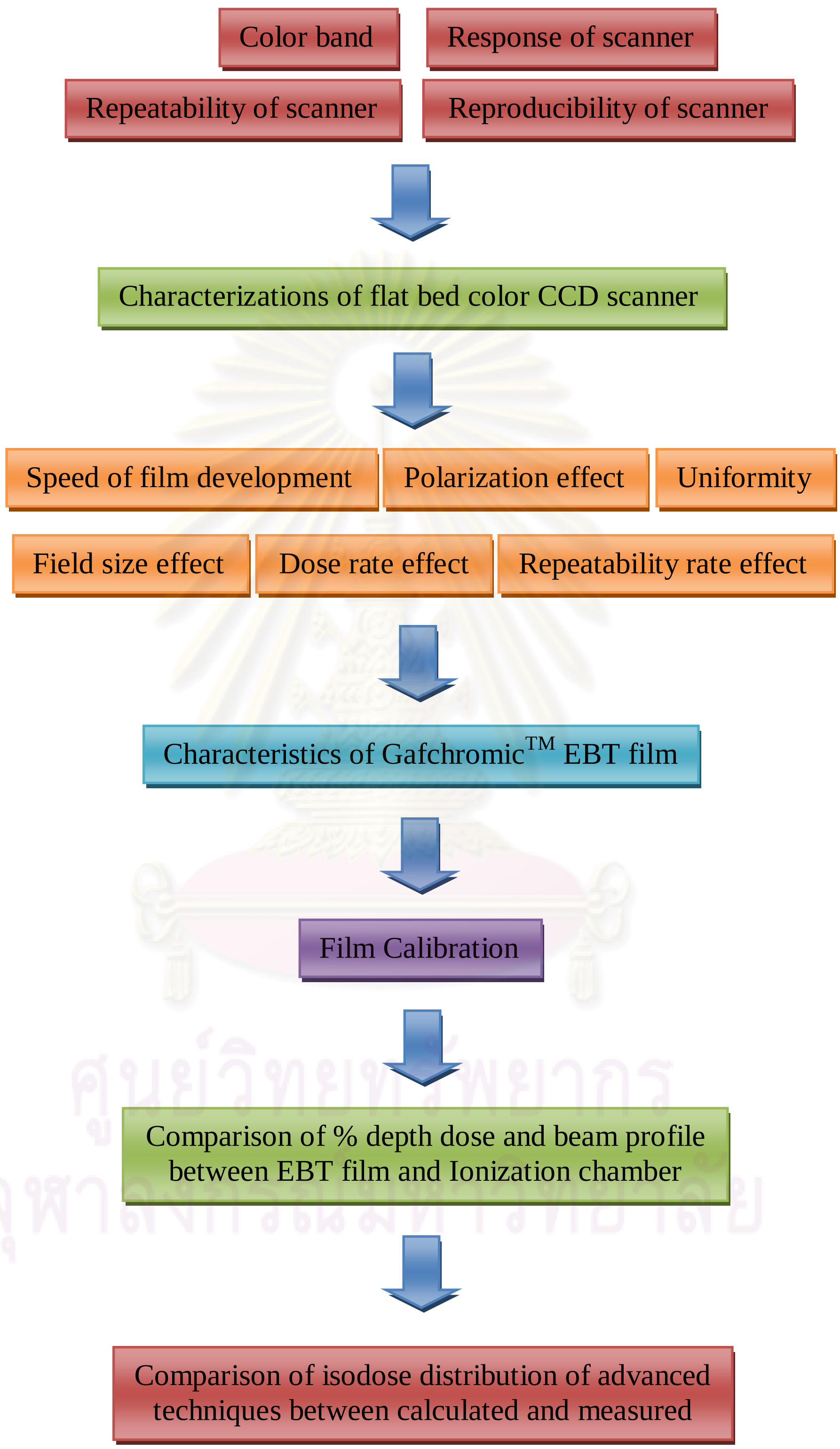


Figure 3.2 conceptual frameworks.

3.4 Key word

- Gafchromic^{TM} EBT film
- Radiochromic film
- Intensity modulation radiotherapy (IMRT)
- Dosimetric verification

3.5 Research questions

3.5.1 Primary question

What are the dosimetric characteristics of Gafchromic^{TM} EBT film for high energy photon beams?

3.5.2 Secondary question

Can the Gafchromic^{TM} EBT film be used for dosimetric verification of advanced radiation treatment techniques?

3.6 Materials

3.6.1 Radiation beams

The Clinac 21EX linear accelerator (Varian Oncology Systems, Palo Alto, CA, USA) gives dual photon beams of 6 MV and 10 MV, and five electron beam energies of 6, 9, 12, 16 and 20 MeV. Photon field sizes are ranged from 0.5×0.5 cm^2 to 40×40 cm^2 at isocenter. The distance from the target to isocenter is 100 cm. There are six stationary therapy dose rates range from 100-600 monitor units per minute. The multileaf collimator (MLC) is mounted below the conventional collimator in the same direction of x-jaws. There are 80 leaves that can move as the dynamic movement.

In this study, we use the 6 MV photon beams from Varian Clinac 21EX linear accelerator and 300 MU/min of dose rate which is available at the Radiotherapy department, Faculty of Medicine of Chulalongkorn University, the machine is shown in figure 3.3.

Figure 3.3 Varian Clinac 21EX linear accelerator.

3.6.2 Scanning densitometer system

The Epson Perfection V700 flat-bed color CCD for EBT film digitization is used as a scanner densitometer. The maximum support of media size is 22×30 cm^2. The color depth of scanner is 48-bit color. The optical resolution of scanner is 6,400 dpi × 9,600 dpi and the maximum resolution is 12,800 dpi × 12,800 dpi of interpolated resolution. It is shown in figure 3.4.

Figure 3.4 Epson Perfection V700 flat-bed CCD scanner.

3.6.3 Virtual water phantom

The virtual water phantom (MedTec, IA, USA) is 1.03 g/cm^3 of the density and 5.97 of atomic number which is made in square slab of 30×30 cm^2 with the thickness of 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 cm. The property of virtual water phantom was investigated by comparing the dose measurement at the same thickness of virtual water phantom and water. The measured dose showed consistent result between the two phantoms. So the thickness correction for virtual water phantom is not needed. The Gafchromic™ EBT film will be placed in solid water slab phantom of 30×30 cm^2 size. They are shown in figure 3.5.

Figure 3.5 Virtual water slab phantom.

3.6.4 Gafchromic™ EBT films

The Gafchromic™ EBT film is an ideal medium for quantitative dosimetry, with spatial resolution better than 0.1 mm and response that is energy and fractionation independent. The EBT film is self-developing and can be handled in room light. The EBT film can also immerse in water. The wide dose range of Gafchromic™ EBT film is 1 cGy to 800 cGy which the EBT film is a pack of 25 sheets. The size of Gafchromic EBT film is 20x25 cm^2.

Figure 3.6 Gafchromic™ film type EBT.

3.6.5 Ion chamber

The 0.13 cm^3 CC13 ionization chamber (Wellhofer Dosimetric, Schwarzenbruck, Germany) can measure absolute and relative dose of photon and electron beams in radiotherapy and can measure in solid water slab phantom or in water phantom. The sensitivity of CC13 is 2.647×10^8 Gy/C. The Ion chamber type 0.13 cm^3 with Dose1 dosimeter will be used in the study for high energy photon beam.

Figure 3.7 Ion chamber type 0.3 cm^3.

3.6.6 Electrometer

The DOSE-1 (Wellhofer Dosimetric, Schwarzenbruck, Germany) is a high precision reference class electrometer that significantly exceeds the recombination of the IEC 60731 and the AAPM ADCLs. It is suitable for the use with ionization chambers, semiconductors and diamond probes. The standard DOSE-1 connects to either TNC or BNC connector types. This electrometer is used with CC13 ionization chamber and is set at 300 V. The maximum charge per pulse is approximate ±40 nC/pulse. The DOSE-1 is shown in figure 3.8.

Figure 3.8 DOSE-1 electrometer.

3.6.7 Blue phantom 3D beam analyzing system

The blue phantom 3D beam analyzing system (Scanditromix Wellhofer Dosimetric, Schwarzenbruck, Germany) is made from acrylic plastic (Perspex), having the scanning volume of 480×480×410 mm^3. It is prepared for external control from the OminiPro-accept 6.4a software (IBA Advanced Radiotherapy, Scanditronix Wellhofer, Uppsala, Sweden). This phantom can be used for percent depth dose, beam profile with CC13 ionization chamber. The blue phantom is shown in figure 3.9.

The blue phantom 3D beam analyzing system comprises a three dimensional high precision servo mechanism and a Perspex water tank. On the horizontal x-rail there is a sliding shoe on which detector holders are in all three dimensions for measuring both horizontal and vertical beams.

Figure 3.9 The 3D beam analyzing system.

3.6.8 Eclipse treatment planning software

Eclipse treatment planning software version 6.4 (Varian Oncology Systems, Palo Alto, CA, USA) is a treatment planning for all modalities such as 3D conformal, IMRT, electron, and brachytherapy. Eclipse helps dosimetrists, physicists, and physicians efficiently create, select, and verify the best treatment plans for their patients. The Eclipse planning software is shown in figure 3.10.

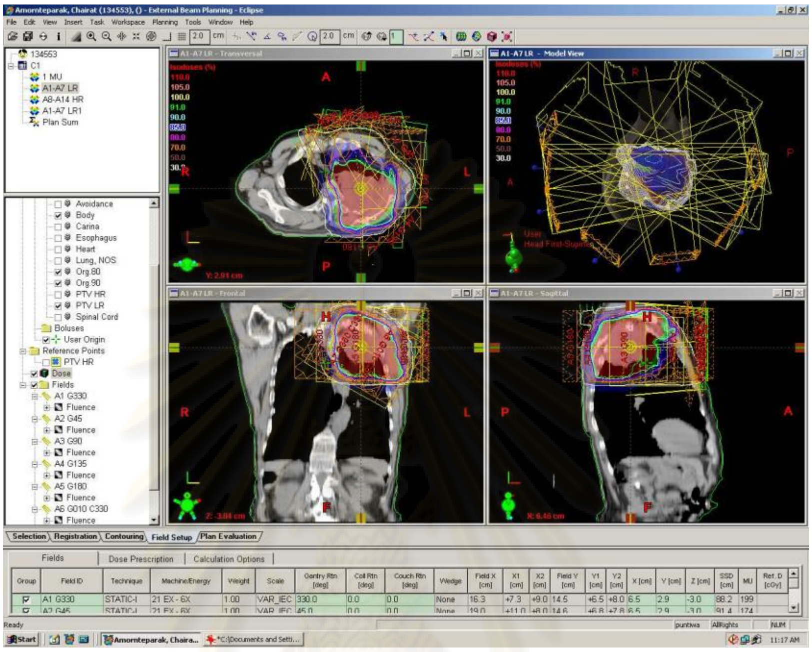


Figure 3.10 Treatment planning from Eclipse planning software.

3.7 Method

The Epson Perfection V700 scanner was warming up by continuous scanning at least five times without a film before studied characteristics of scanner and Gafchromic^{TM} EBT films. The pixel values were read by Image J software for 1.5×1.5 cm^2 ROI at center of irradiated film. Then, the net optical densities were calculated from equation of (2-2) by Microsoft Excel program.

3.7.1 The characteristics of Epson Perfection V700 scanner

3.7.1.1 The response of flat-bed color scanner

The standard step wedge film was scanned by using 75 spatial resolution and 48 bit-depth scanner. Then, the response of scanner was plotted by pixel value measurement and optical density of standard step wedge film. The standard pattern of step wedge film is shown in figure 3.11.

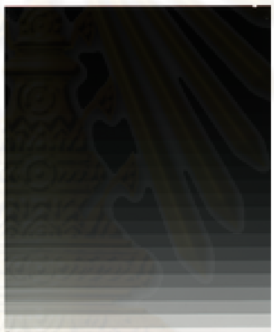


Figure 3.11 The standard step wedge pattern.

3.7.1.2 The repeatability and reproducibility of flat-bed scanner

The standard pattern of step wedge film in figure 3.11 was scanned with the one band of 1.55 optical density for five days, ten times continuously each day for reproducibility and repeatability verification. Then, the graph was plotted between the net optical density and the scan number.

3.7.1.3 Color band

The films size of 3×3 cm^2 were placed horizontally inside solid slab phantom for field size of 10×10 cm^2 at 1.5 cm depth, 20 cm back scatter and 100 cm SSD. The direction of films was marked by permanent marker. Then, the EBT films were irradiated to the following doses of: 10, 20, 50, 100, 150, 200, 250, 300, 400, 500, 600 and 700 cGy, respectively with 6 MV photon beam on Varian Clinac 21EX linear accelerator. The exposed films were measured by three channels band color (red: 622-780 nm, green: 492-577 nm and blue: 445-492 nm) then the outcomes of data were plotted between doses and net optical density.

3.7.2 The characteristics of Gafchromic^{TM} EBT films

The Gafchromic^{TM} EBT films were cut into 3×3 cm^2 size for studying of characteristics of EBT films such as: speed of films development, field sizes effect, dose rate effect and repeatability rate effect. The EBT films size of 20×25 cm^2 were used for film uniformity, polarization effect, beam profile, percentage depth dose and IMRT planning verification.

3.7.2.1 Speed of films development

The films size of 3×3 cm^2 were placed horizontally inside solid slab phantom for field size of 10×10 cm^2 at 1.5 cm depth, 20 cm back scatter and 100 cm SSD. Then, the EBT films were irradiated to the following doses of: 50, 100, 200 and 400 cGy, respectively with 6 MV photon beam. The irradiated films were studied by varying time for two intervals. The first interval was separated by 10 minutes for 180 minutes (3 hours) period. The second interval was separated by 1 hour for 6 hours period. The results of measurement were plotted between relative net optical density and elapsed time.

3.7.2.2 Polarization effect

The EBT films of “20×25 cm^2 size” were placed horizontally inside solid slab phantom for field size of 30×30 cm^2 at 5 cm depth, 20 cm back scatter and 100 cm SSD, it is shown in figure 3.12. The direction of films was marked by permanent marker. Then, the EBT films were irradiated to the following doses of: 50, 100, 200 and 400 cGy, respectively with 6 MV photon beam. The irradiated films were scanned for five directions for 0^0, 90^0, 180^0, 270^0 and 180^0- flip. The results of scan were plotted between relative net optical density and orientation angle.

3.7.2.3 Uniformity

The exposed films for polarization effect were used to study the uniformity, it was scanned and the pixel values for region of interest (ROI) of 18×18 cm^2 size were recorded. The profiles were plotted between normalized pixel value and distance.

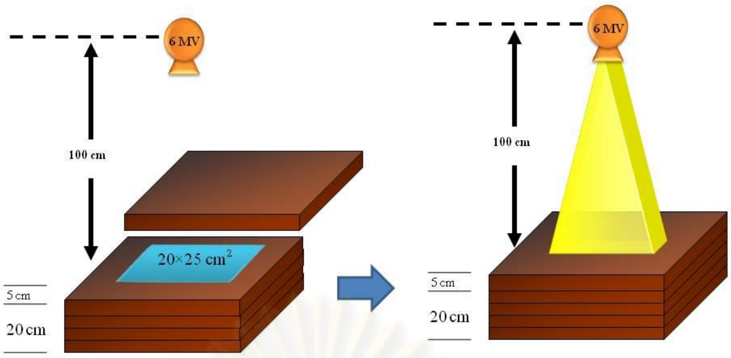


Figure 3.12 Set up for polarization and uniformity measurements.

3.7.2.4 Field size effects

The films size of 3×3 cm^2 were placed horizontally inside solid slab phantom for at 1.5 cm depth, 20 cm back scatter and 100 cm SSD. Then, the EBT films were irradiated for field sizes of 2×2 cm^2, 5×5 cm^2, 10×10 cm^2, 15×15 cm^2 and 25×25 cm^2 with 100 cGy dose which shows in figure 3.13. The output factor was calculated. The data measurements were plotted between sizes of square field and output factor. Then, the output factors of the EBT films measurement were compared with CC13 ionization chamber measurement.

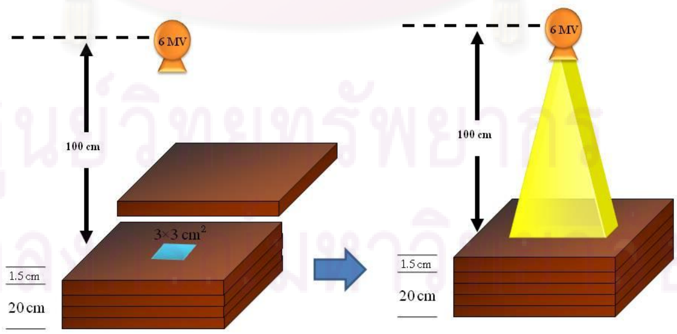


Figure 3.13 Set up for field sizes effect measurement.

3.7.2.5 Dose rate effect

The films size of 3×3 cm^2 were placed horizontally inside solid slab phantom for field size of 10×10 cm^2 at 1.5 cm depth, 20 cm back scatter. The direction of films was marked by permanent marker. Then, the EBT films were exposed by varying distance for 80, 90, 100, 110 and 120 cm source skin distance (SSD) with 200 cGy doses. The pixel values were obtained with the real time measurement and after 24 hour irradiated EBT film. The data of film measurement were plotted between dose rate (208.33 cGy/min to 467.75 cGy/min) and relative sensitivity normalized to dose rate of 300 cGy/min for 10×10 cm^2 field size.

3.7.2.6 Repeatability rate effect

The films size of 3×3 cm^2 were placed horizontally inside solid slab phantom for field size of 10×10 cm^2 at 1.5 cm depth, 20 cm back scatter. Then, the EBT films were exposed by varying monitor unit rate for 100, 200, 300, 400, 500 and 600 MU/min with 100 cGy dose. The data of film measurement were plotted between relative net optical density normalized to repeatability rate of 300 MU/min and repeatability rate. Also, the relative sensitivity of EBT films with repeatability rate was compared with the relative sensitivity of CC13 ionization chamber measurement.

3.7.3 The sensitometric curve of Gafchromic™ EBT film

The Gafchromic™ EBT films were cut into 3×3 cm^2 size. The EBT films were placed horizontally inside solid slab phantom for field size of 10×10 cm^2 at 1.5 cm depth, 20 cm back scatter and 100 cm SSD. The direction of films was marked by permanent marker. Then, the EBT films were irradiated to the following doses of: 10, 20, 50, 100, 150, 200, 250, 300, 400, 500, 600 and 700 cGy, respectively with 6 MV photon beam on Varian Clinac 21EX linear accelerator which is shown in figure 3.14. A sensitometric curve was plotted between net optical density and doses.

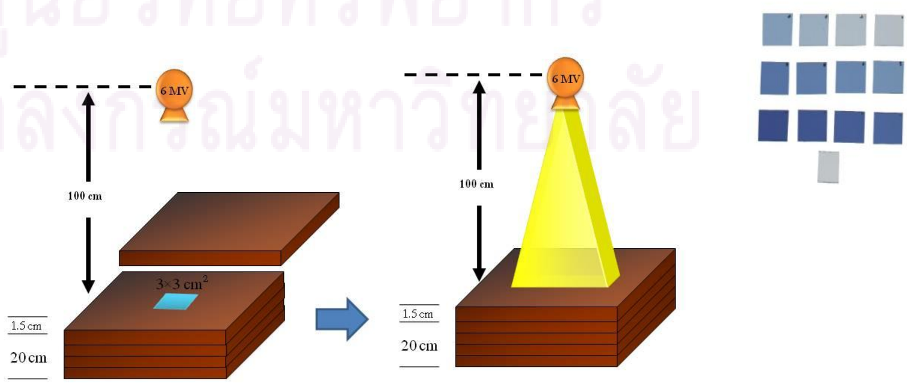


Figure 3.14 Set up for dose sensitometric curve measurement.

3.7.4 Percentage depth dose and beam profile

The Gafchromic™ EBT films of 20×25 cm^2 size were horizontally placed inside solid slab phantom at 100 cm SSD. The edge of EBT films were aligned at the edge of phantom which is demonstrated in figure 3.15. The EBT films were exposed for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×0 cm^2, respectively. The EBT films were analyzed by MapCHECK version 3.05.02.

The beam profiles of EBT film were studied for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×0 cm^2 at 5 cm depth and then compared with beam profiles of CC13 ionization chamber at the same depth. The percentage depth doses of EBT film were compared with CC13 ionization chamber for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×0 cm^2, respectively.

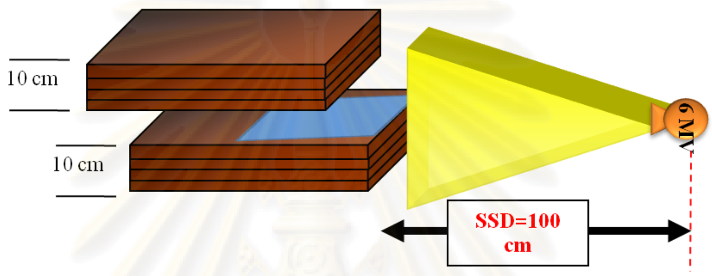


Figure 3.15 The EBT film set up for percentage depth dose and beam profile measurement.

3.7.5 Dose verification analysis

The Gafchromic™ EBT films were verified with three IMRT complex treatments planning for 6 MV photon beams from Varian Clinac 21EX linear accelerator. The Gafchromic™ EBT film was placed horizontal inside solid slab water phantom at 5 cm depth for IMRT plan with 20 cm of back scatter thickness. The EBT films were irradiated with two nasopharynx and one brain tumor cancer of IMRT composite plans from Eclipse treatment planning. The irradiated EBT film was waited for 24 hour after exposed film. Then, the EBT film was analyzed with MapCHECK software. The percent passed of IMRT treatment planning was analyzed by Gamma index which accepted with percent dose different of 3% and 3 mm distance to agreement.

3.8 Outcome measurement

Variable: independent variables = Energy, depth, field size
: Dependent variables = Net optical density, pixel value, dose

3.9 Data collection

The pixel values were read by Image J software at central of irradiated film. Then, the net optical densities were calculated from equation of (2-2) by Microsoft Excel program.

3.10 Data analysis

In a series of n measurements, with observed values x_i, the best estimate of the quantity x is usually given by the arithmetic mean value$(\bar{x})$.

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3\text{-}1)$$

The equation for determining the percent difference, (assuming both x_1 and x_2 are positive), by comparing values x_1 and x_2 is:

$$\%Diff = \frac{|x_1 - x_2|}{((x_1+x_2)/2)} \times 100 \qquad (3\text{-}2)$$

Percent error seems the general standard of calculating the percent error involves using the absolute function imposed on the difference between the experimental (measured) and accepted (actual) values. However, this removes detail from the result in the form of only producing a positive percent error value. It should be suggested to ignore the absolute function and calculate the percent error as follows,

$$\%Error = \frac{Exp - Acpt}{Acpt} \times 100 \qquad (3\text{-}3)$$

The numerator should be the Experimental value minus the Accepted value and *not* the other way around. By using the equation shown above, the result will be positive only when the experimental value is greater than the accepted and the result will be negative only when the experimental value is less than the accepted.

This is a very important outcome. By avoiding the absolute function when calculating for the percent error, the results will give both the reader and author more information. If the percent error is negative, the reader knows immediately that the experimental value is short of the accepted (goal) value. If the percent error is positive, the reader knows that the experimental value is above the accepted (goal) value. This technique of solving the percent error value becomes very helpful whenever an accepted value imposes a lower or upper limit for all experimental (measured) values.

The sensitometric curve was plotted between net optical density and dose. The beam profile and percentage depth dose from CC13 ionization chamber were compared with beam profile and percentage depth dose from EBT film measurement.

The verifications of IMRT composite plan of nasopharynx cancer and brain tumor were demonstrated by gamma index for the agreement between calculated and measured dose distributions, the gamma parameter has been adopted, as generally accepted the reference values for the agreements are 3% of dose and 3 mm of distance. The software includes the gamma evaluation analysis of the result.

3.11 Benefit of the study

- Determine the dosimetric characteristics of Gafchromic EBT film for high energy photon beams.
- Determine the optical parameters for EBT film calibration.
- Used EBT films for verification isodose distribution of advanced radiation treatment techniques.

3.12 Ethical consideration

Although this study will be performance in phantom, however the ethical approval was processed by Ethics Committee of Faculty of medicine, Chulalongkorn University.

CHAPTER IV

RESULTS

The characteristics of Epson Perfection V700 flat-bed scanner must be investigated before studying the characteristics of Gafchromic^{TM} EBT films, they are: the response, repeatability, reproducibility and color band. The relation of optical density and pixel value should be known for using the film properly.

4.1 The characteristics of flat-bed color scanner

4.1.1 The response of flat-bed color scanner

The relation between net optical density and pixel value of standard step wedge film is shown in table 4.1, the graph in figure 4.1 shows the polynomial response. The pixel value illustrated less change when net optical density was more than 1.0.

Table 4.1 The data of net optical density values and pixel value of standard step wedge film.

Average of Pixel Values	Net Optical Density	Average of Pixel Values (Cont.)	Net Optical Density (Cont.)
65535.00	0.00	3980.35	1.22
60787.95	0.03	3247.92	1.31
49399.92	0.12	2597.57	1.40
38700.70	0.23	2329.74	1.45
31121.38	0.32	1929.61	1.53
25222.77	0.42	1554.52	1.63
19627.49	0.52	1317.62	1.70
15116.03	0.64	1110.19	1.77
12002.69	0.74	951.87	1.84
9559.81	0.84	829.07	1.90
7620.29	0.94	733.01	1.95
6180.72	1.03	684.86	1.98
5008.30	1.12	669.94	1.99

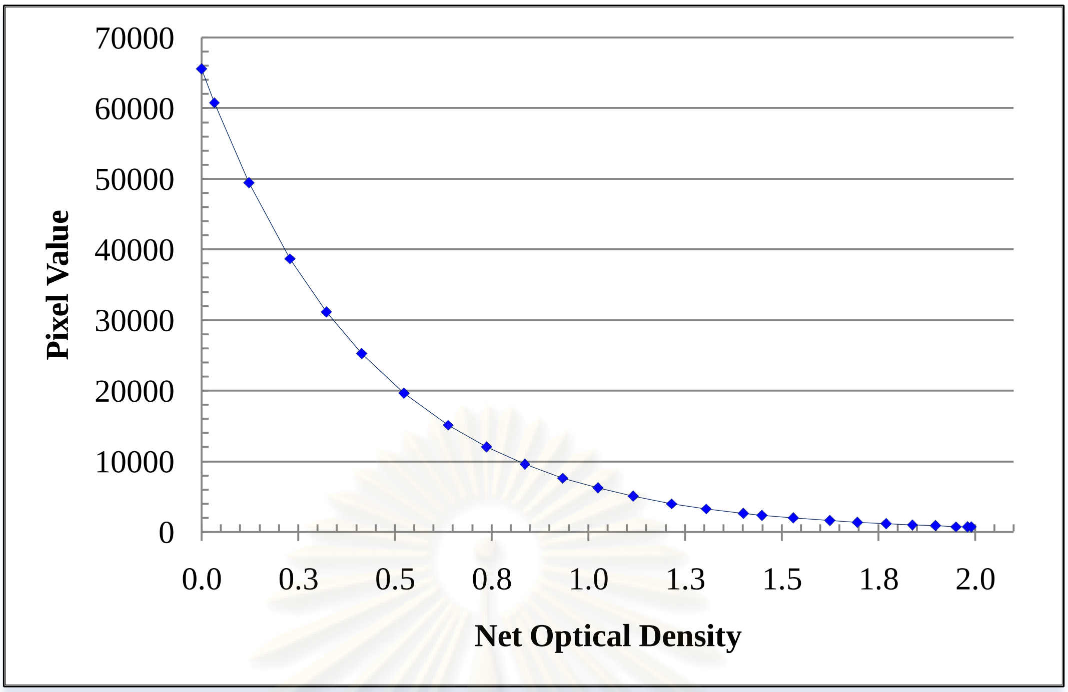


Figure 4.1 The response of Epson Perfection V700 scanner.

4.1.2 The repeatability and reproducibility of flat-bed color scanner

The repeatability for ten times reading and reproducibility for five days which were shown in term of normalized net optical density to the first scan of the first day are illustrated in table 4.2 and figure 4.2. The variation for ten times repeat readings for five days was within 1.1%. The response showed the trend of lower value for the higher scan number.

Table 4.2 The variation of ten times continuous scanning for five days. The reading was normalized to the first scan of the first day.

Scan Number	1st day	2nd day	3rd day	4th day	5th day
1	1.000	0.996	1.008	1.003	1.004
2	1.002	0.996	1.006	1.001	1.002
3	1.003	0.999	1.004	1.002	1.008
4	0.998	0.995	1.006	1.006	1.006
5	1.000	0.993	1.003	0.999	1.009
6	1.002	0.993	1.003	0.998	1.005
7	1.001	0.994	1.005	0.997	1.004
8	1.000	0.992	1.002	0.997	0.999
9	1.000	0.993	1.002	0.996	0.999
10	0.999	0.992	1.002	0.998	0.998
Mean	1.001	0.994	1.004	1.000	1.003

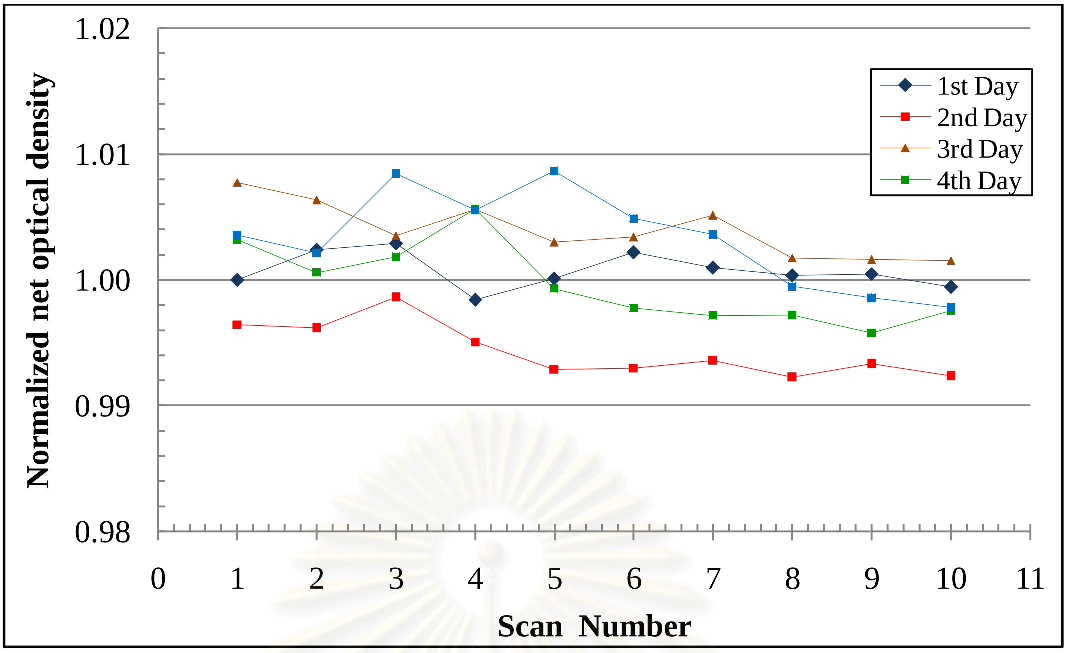


Figure 4.2 The repeatability and reproducibility of Epson Perfection V700 flat-bed scanner.

4.1.3 The color band

The relation between doses and net optical density of red, green and blue color channels are shown in table 4.3 and figure 4.3. The red channel demonstrated highly sensitive response, so the red channel is used in this research.

Table 4.3 The net optical density of red, green and blue channels for various doses.

Set dose (cGy)	Net Optical Density		
	Red channel	Green channel	Blue channel
0	0.000	0.000	0.000
10	0.079	0.065	0.056
20	0.109	0.078	0.040
50	0.196	0.143	0.065
100	0.288	0.229	0.115
150	0.343	0.288	0.165
200	0.368	0.317	0.171
250	0.393	0.347	0.193
300	0.415	0.377	0.223
400	0.446	0.421	0.271
500	0.455	0.439	0.287
600	0.469	0.459	0.310
700	0.482	0.480	0.338

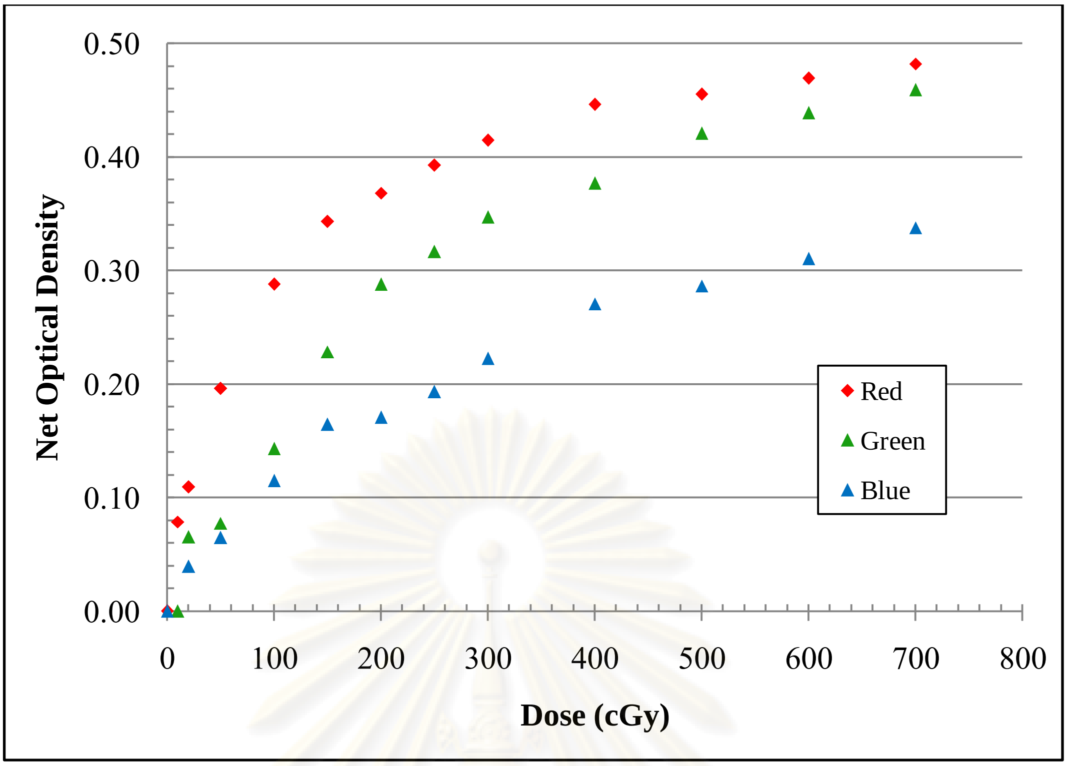


Figure 4.3 The sensitivity responds curve of Gafchromic™ EBT film in red, green and blue channel with the dose range of 0 to700 cGy.

4.2. The characteristics of Gafchromic^{TM} EBT film

4.2.1 Speed of EBT films development

The speeds of EBT film development for 9 hours in table 4.4 and figure 4.4 show the stability about 4 hours after irradiation. The net optical densities of 50, 100, 200 and 400 cGy were increasing up to 7.1%, 6.4%, 6.2% and 4.9%, respectively for intervals of 0 hour to 9 hours. The lower dose presented more change of net optical density than higher dose.

Table 4.4 The response of EBT film development in term of net optical density for various doses of 50, 100, 200 and 400 cGy.

Time (minute)	Net OD/OD(t=0)			
	50 cGy	100 cGy	200 cGy	400 cGy
10	1.012	1.009	1.012	1.009
20	1.019	1.017	1.018	1.014
30	1.021	1.024	1.019	1.017
40	1.028	1.027	1.027	1.023
50	1.032	1.031	1.031	1.024
60	1.037	1.034	1.035	1.027
70	1.038	1.038	1.037	1.030
80	1.041	1.040	1.039	1.032
90	1.047	1.043	1.043	1.034
100	1.046	1.046	1.043	1.033
110	1.048	1.047	1.046	1.038
120	1.049	1.048	1.046	1.037
130	1.053	1.050	1.048	1.039
140	1.055	1.052	1.051	1.043
150	1.058	1.054	1.053	1.044
160	1.061	1.057	1.054	1.044
170	1.064	1.058	1.057	1.046
180	1.062	1.060	1.057	1.043
4 hours	1.071	1.064	1.062	1.049
5 hours	1.066	1.061	1.060	1.048
6 hours	1.067	1.063	1.060	1.051
7 hours	1.066	1.064	1.060	1.048
8 hours	1.060	1.064	1.059	1.044
9 hours	1.061	1.062	1.057	1.046

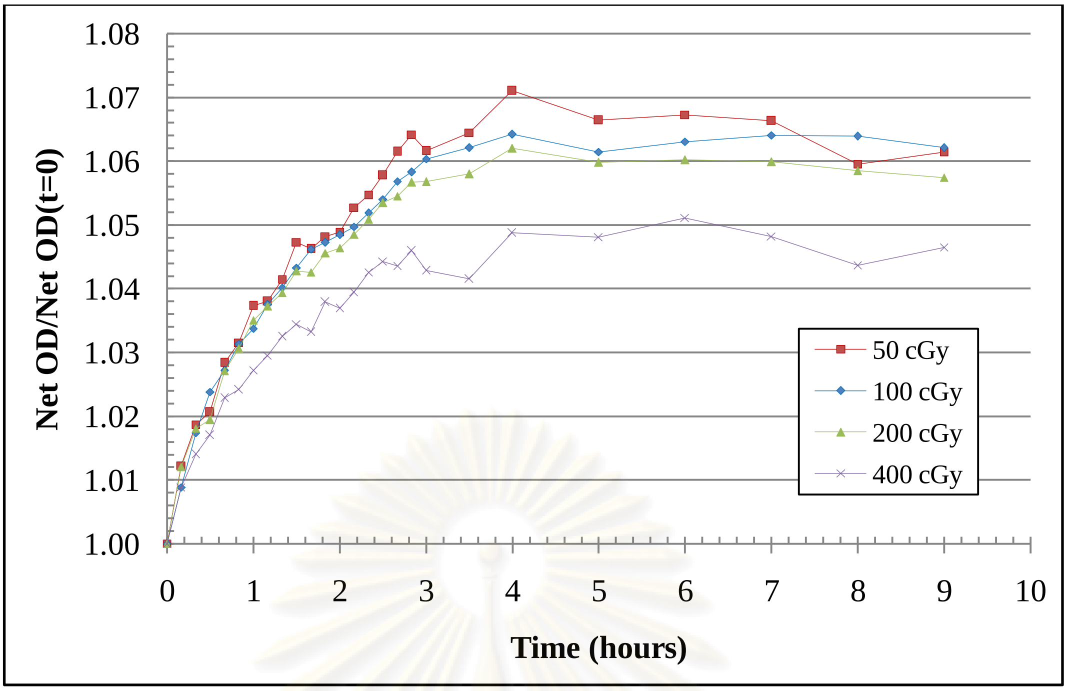


Figure 4.4 The speed of EBT film development for the interval of 9 hours.

4.2.2 Polarization effect

The relation between net optical density and film orientation is shown in table 4.5a , the normalized net optical density to zero degree orientation at different orientation of film with various doses are shown in table 4.5b and figure 4.5. The lower normalized netOD at 90^0 and 270^o orientations illustrated the polarization but it was not occurred at 0^o, 180^o and 180^o-flip. The effect of EBT film polarizations was depending on the quantity of doses, high dose had less effect than small dose. The variation due to dose dependent was about 5% for 400 cGy to 24% for 50 cGy.

Table 4.5a The net optical density and film orientation at various doses.

Orientation (Degree)	Net optical density			
	50 cGy	100 cGy	200 cGy	400 cGy
0	0.189	0.274	0.354	0.422
90	0.144	0.237	0.324	0.402
180	0.191	0.275	0.354	0.422
270	0.145	0.240	0.326	0.403
180-flip	0.191	0.275	0.354	0.422

Table 4.5b The normalized net optical density and film orientations at various doses.

Orientation (Degree)	Normalized net optical density			
	50 cGy	100 cGy	200 cGy	400 cGy
0	1.000	1.000	1.000	1.000
90	0.760	0.865	0.915	0.952
180	1.009	1.002	1.000	1.000
270	0.768	0.877	0.922	0.955
180-flip	1.008	1.004	1.001	0.999

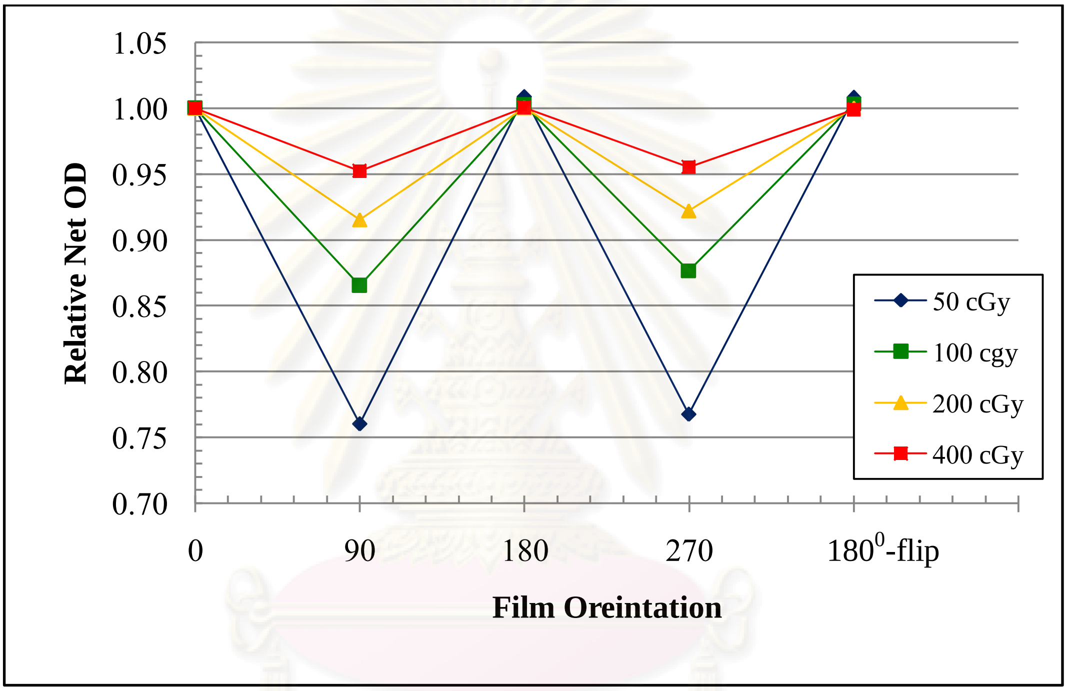


Figure 4.5 The polarization effect of Gafchromic^{TM} EBT film at 0^o, 90^o, 180^o, 270^o, 180^o-flip degree.

4.2.3 Uniformity

The non-uniformity of pixel value normalized to center of beam was about ±7%, for 18×18 cm^2 region of interest (ROI), the result is shown in figure 4.6. This effect is due to the non-uniformity of both Gafchromic™ EBT film and Epson Perfection V700 scanner. The small dose presented non-uniformity effect of pixel value less than high dose. The maximum difference of normalized pixel value between 50 cGy dose and 400 cGy doses at the edge of region of interest was 3%.

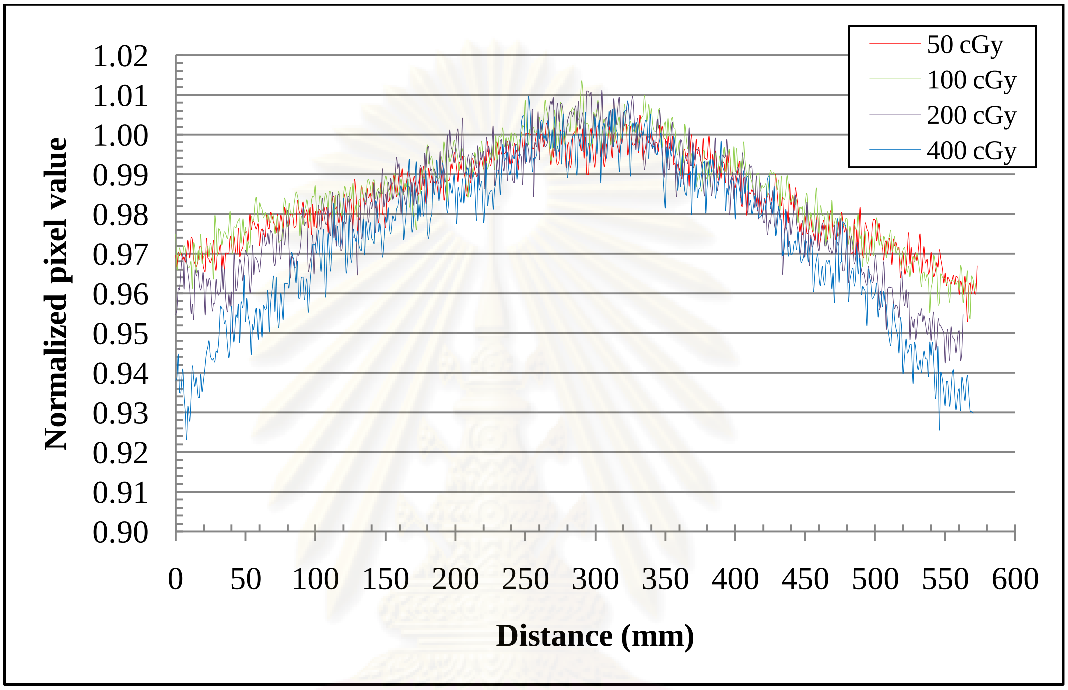


Figure 4.6 The non-uniformity of Gafchromic™ EBT film at various doses of 50,100,200 and 400 cGy.

4.2.4 Field size effects

The output factors measured by Gafchromic™ EBT film and by ionization chamber are shown in Table 4.6 and figure 4.7. The maximum of percentage difference between Gafchromic™ EBT film and CC13 ionization measurement was 2.01%, it occurred at small field size and was comparable for field size of larger than 10×10 cm^2.

Table 4.6 The output factors of Gafchromic™ EBT film and CC13 Ion chamber.

Sizes of square filed (cm)	Film output factor	Ion chamber output factor	% Difference
2	0.901	0.886	1.69
5	0.965	0.946	2.01
10	1.000	1.000	0.00
15	1.029	1.032	0.29
25	1.062	1.065	0.28

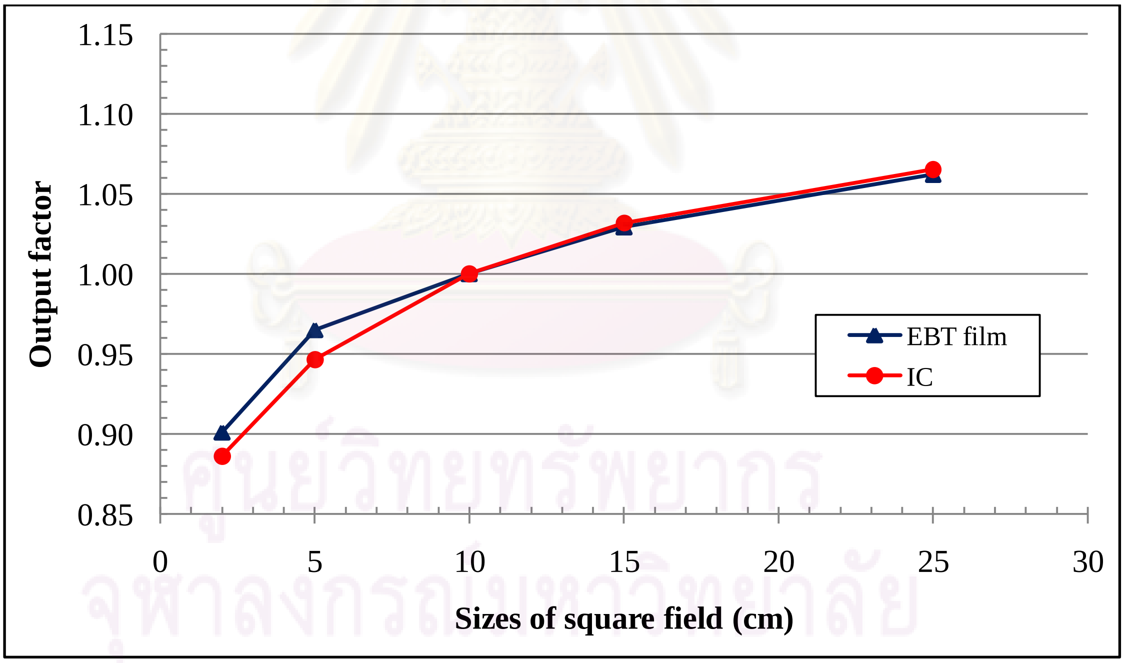


Figure 4.7 Output factors of 6 MV photon beams obtained by Gafchromic™ EBT film and CC13 ionization chamber at 1.5 cm depth, 100 cm SSD.

4.2.5 Dose rate effect

The relation between pixel value and dose rates of Gafchromic^{TM} EBT film is shown in table 4.7a, the normalized pixel value to 300 cGy/min at various dose rates present in table 4.7b and figure 4.8 illustrated agreements within 0.3 % for real time measurement and about 1% after 24 hours irradiated EBT film. The sensitivity of Gafchromic^{TM} EBT film at smaller dose rate was higher than larger dose rate.

Table 4.7a The response of Gafchromic^{TM} EBT film for various dose rates for 200 cGy dose of 6 MV photon beams for field size of 10×10 cm^2 at 1.5 cm depth.

Dose rate (cGy/min)	Real time measurement	After 24 hours measurement
468.75	28448.04	48119.68
370.37	28549.21	27588.77
300.00	28537.47	27805.03
247.93	28596.52	27621.38
208.33	28616.86	27796.41

Table 4.7b The normalized response measurements at various dose rates.

Dose rate (cGy/min)	Normalized response measurement		
	Real time of EBT measurement	After 24 hours of EBT measurement	CC13 Ion chamber measurement
468.75	0.997	0.998	0.991
370.37	1.000	1.006	0.996
300.00	1.000	1.000	1.000
247.93	1.002	1.006	1.005
208.33	1.003	0.999	1.008

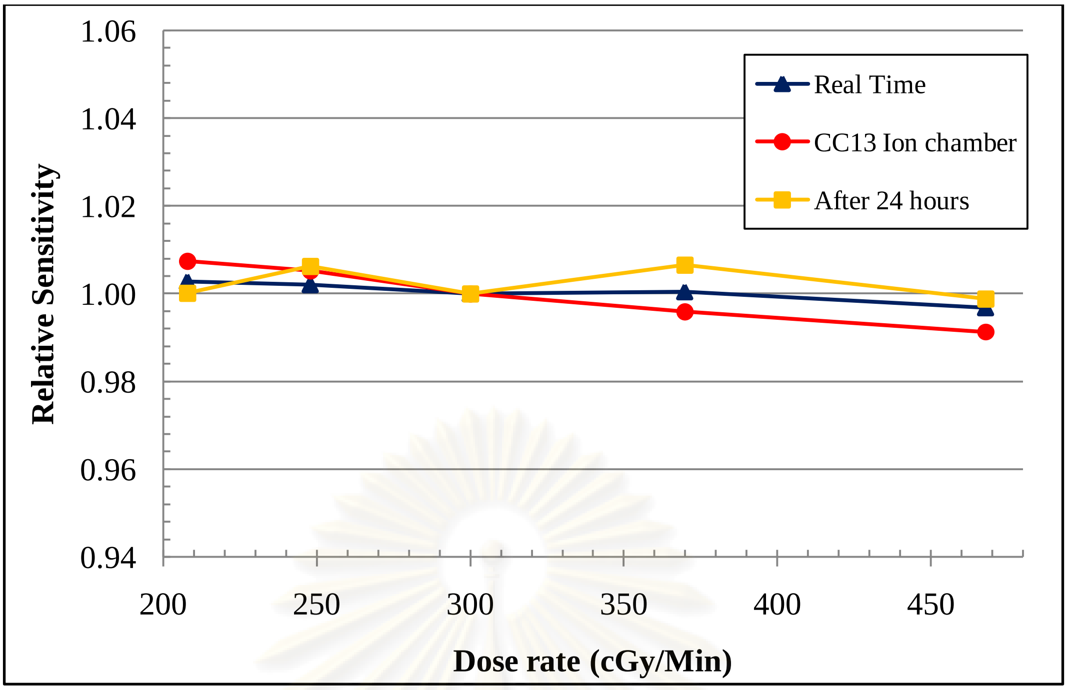


Figure 4.8 The sensitivity of Gafchromic^{TM} EBT film for various dose rates.

4.2.6 Repeatability rate effect

The relation between pixel value and repeatability rates of Gafchromic^{TM} EBT film is shown in table 4.8a, the normalized pixel value to 300 MU/min at various repeatability rates present in table 4.8b and figure 4.9 showed agreeable within 0.4% after 24 hours irradiated. There was more effect at small repeatability rate than large repeatability rate.

Table 4.8a The responses of Gafchromic^{TM} EBT film and CC13 ionization chamber for various repeatability rates for 100 cGy dose of 6 MV photon beams for field size of 10×10 cm^2 at 1.5 cm depth.

Repeatability rate (MU/min)	The response measurements	
	EBT film (Pixel value)	CC13 ion chamber (nC)
100	37348.861	3.750
200	37371.484	3.739
300	37317.084	3.731
400	37242.260	3.727
500	37205.111	3.723
600	37258.417	3.727

Table 4.8b The normalized response measurements and various repeatability rates.

Repeatability rate (MU/min)	Normalized response measurements	
	EBT film (Pixel value)	CC13 ion chamber (nC)
100	0.996	1.005
200	0.999	1.002
300	1.000	1.000
400	0.999	0.999
500	0.999	0.998
600	0.999	0.999

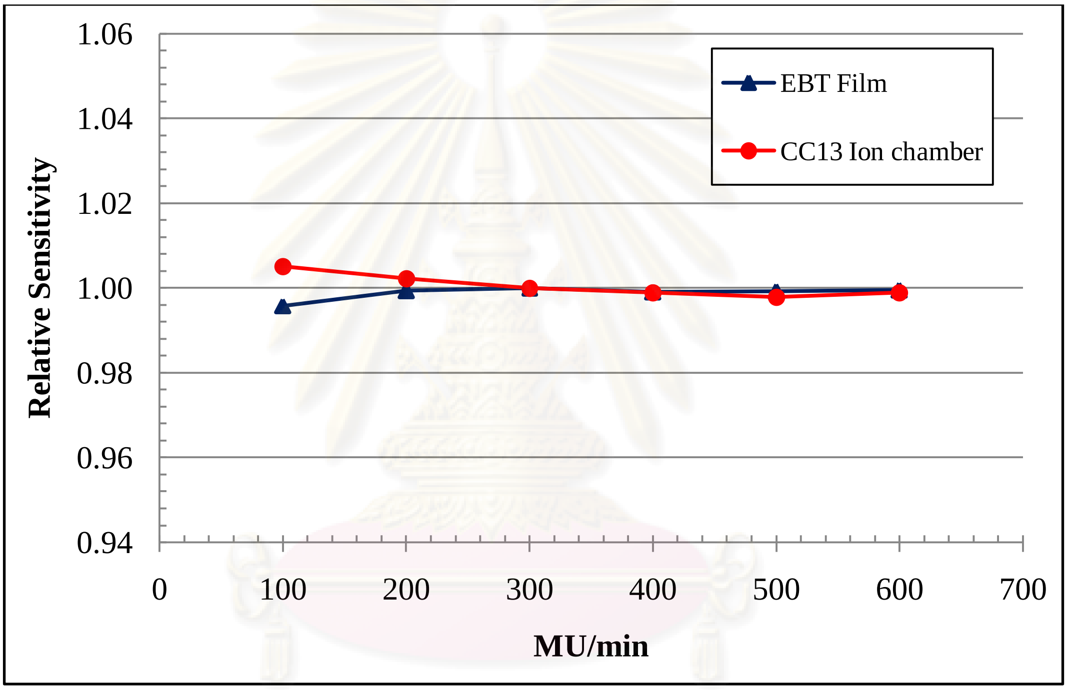


Figure 4.9 The repeatability rate effect of 100 cGy dose of 6 MV photon beams obtained by Gafchromic^{TM} EBT film for field size of 10×10 cm^2 at 1.5 cm depth.

4.3 The sensitometric curve of Gafchromic^{TM} EBT film

The sensitometric curve which is illustrated in table 4.9 and figure 4.10 was plotted between net optical densities and dose. It is shown as a third-order polynomial fitted curve. The curve changed less at dose larger than 400 cGy at net optical about 0.42. The suitable dose range should not be greater than 400 cGy of advanced techniques.

Table 4.9 The sensitometric curve data of Gafchromic^{TM} EBT film.

Dose (cGy)	Pixel Value	Net optical density
0	65535.000	0.000
10	46535.817	0.042
20	44937.098	0.077
50	40145.364	0.168
100	34183.484	0.259
150	29982.149	0.314
200	27469.748	0.343
250	25337.067	0.367
300	23242.418	0.389
400	19880.304	0.422
500	18421.550	0.436
600	17123.717	0.448
700	15690.907	0.461

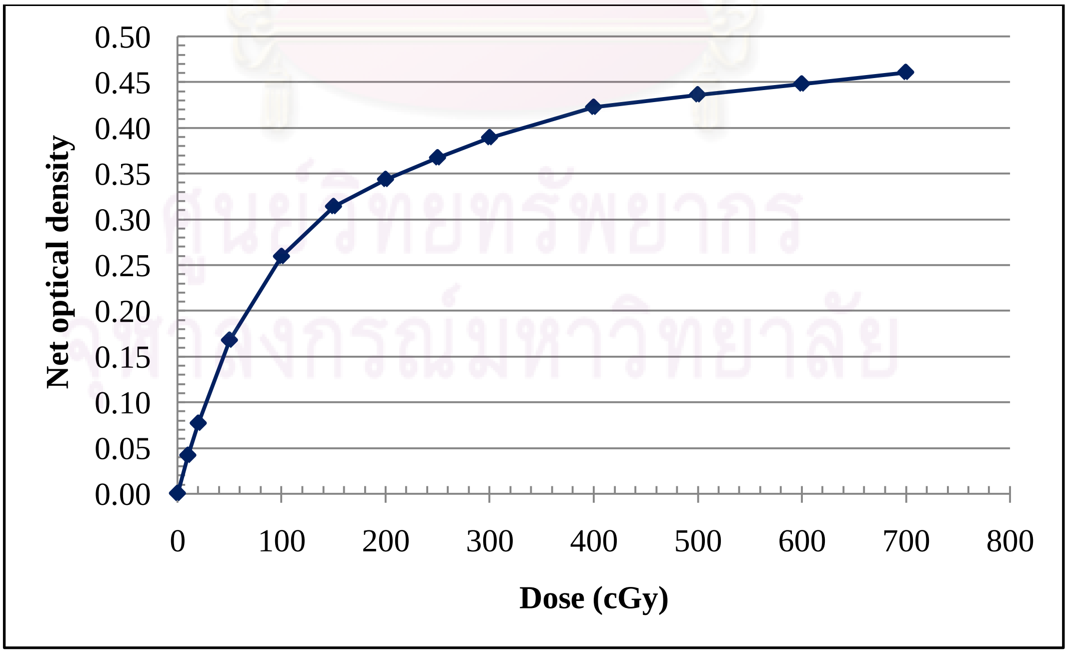


Figure 4.10 The characteristic curve of Gafchromic^{TM} EBT film at dose of 50 – 700 cGy for field size of 10×10 cm^2 at 1.5 cm depth.

4.4 Percentage depth dose and beam profile

The percentage depth dose were measured by Gafchromic™ EBT film in solid water phantom compared with CC13 Ion chamber for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2, respectively. The percent difference of percentage depth dose between EBT film and CC13 Ion chamber for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2 show in table 4.10, table 4.11 and table 4.12, respectively. The depth dose curves of EBT film and CC13 Ion chamber for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2 are shown in figure 4.11, figure 4.12 and figure 4.13, respectively. The discrepancies of EBT film and CC13 at 5 cm depth were 3.11%, 0.64% and 1.12% for field sizes of 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2, respectively.

Table 4.10 The comparison of percentage depth dose measured with Gafchromic™ EBT film to that measured with CC13 Ion chamber for the field size of 2×2 cm^2.

Depth (cm)	Percentage depth dose		% Difference
	CC13 Ionization chamber	Gafchromic™ BBT film	
1.5	100.00	100.00	
5	81.84	79.29	3.11
10	58.99	58.78	0.35
15	43.30	42.7	1.38

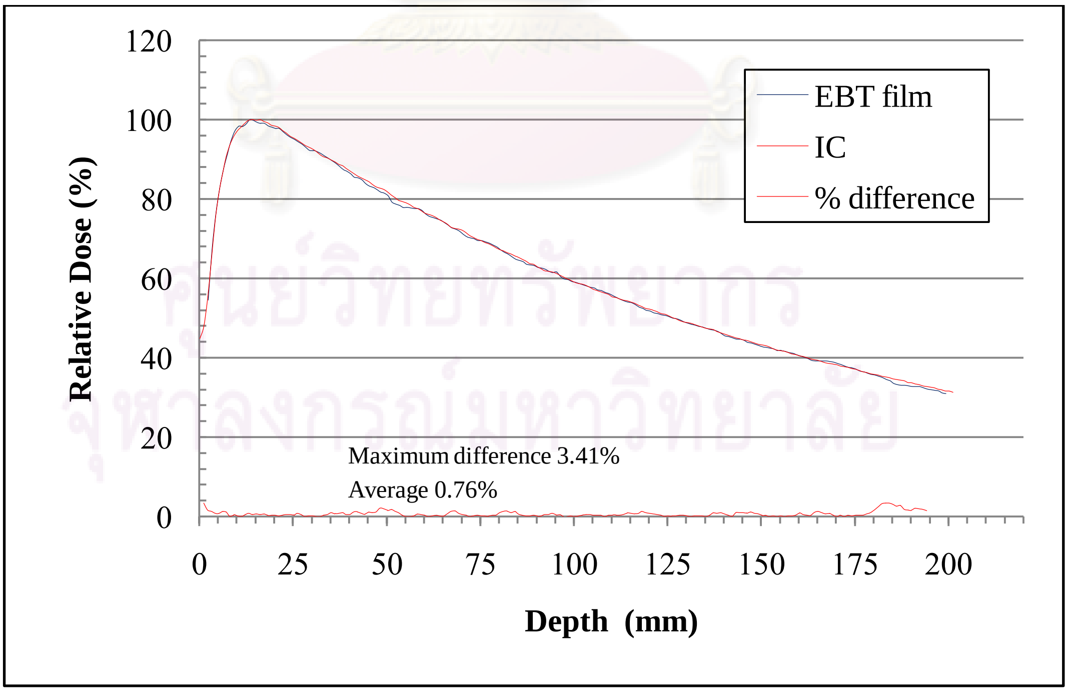


Figure 4.11 The comparison of percentage depth dose studied by Gafchromic™ EBT film and CC13 Ionization chamber for 2×2 cm^2 of field size.

Table 4.11 The comparison of percentage depth dose measured with Gafchromic^{TM} EBT film to that measured with CC13 Ion chamber for the field size of 6×6 cm^2.

Depth (cm)	Percentage depth dose		% Difference
	CC13 Ionization chamber	Gafchromic^{TM} BBT film	
1.5	100.00	100.00	
5	85.44	84.89	0.64
10	64.19	64.57	0.59
15	47.89	47.1	1.64

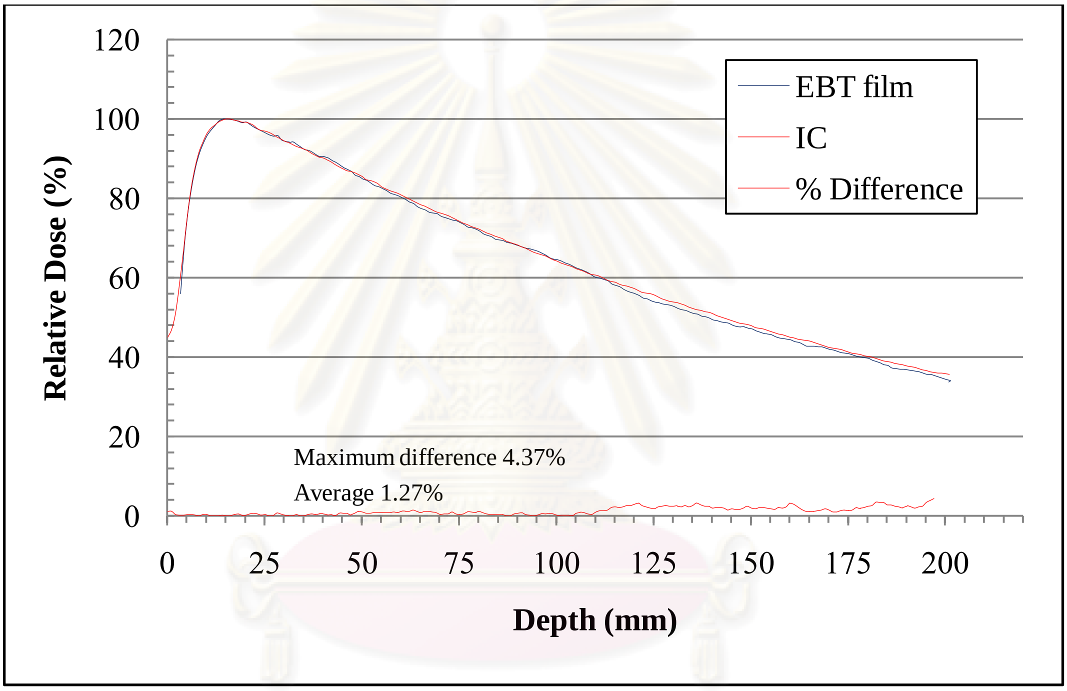


Figure 4.12 The comparison of percentage depth dose studied by Gafchromic^{TM} EBT film and CC13 Ionization chamber for 6×6 cm^2 of field size.

Table 4.12 The comparison of percentage depth dose measured with Gafchromic™ EBT film to that measured with CC13 Ion chamber for the field size of 10×10 cm^2.

Depth (cm)	Percentage depth dose		% Difference
	CC13 Ionization chamber	Gafchromic™ BBT film	
1.5	100	100.00	
5	85.95	84.98	1.12
10	66.39	65.27	1.68
15	50.68	49.16	2.99

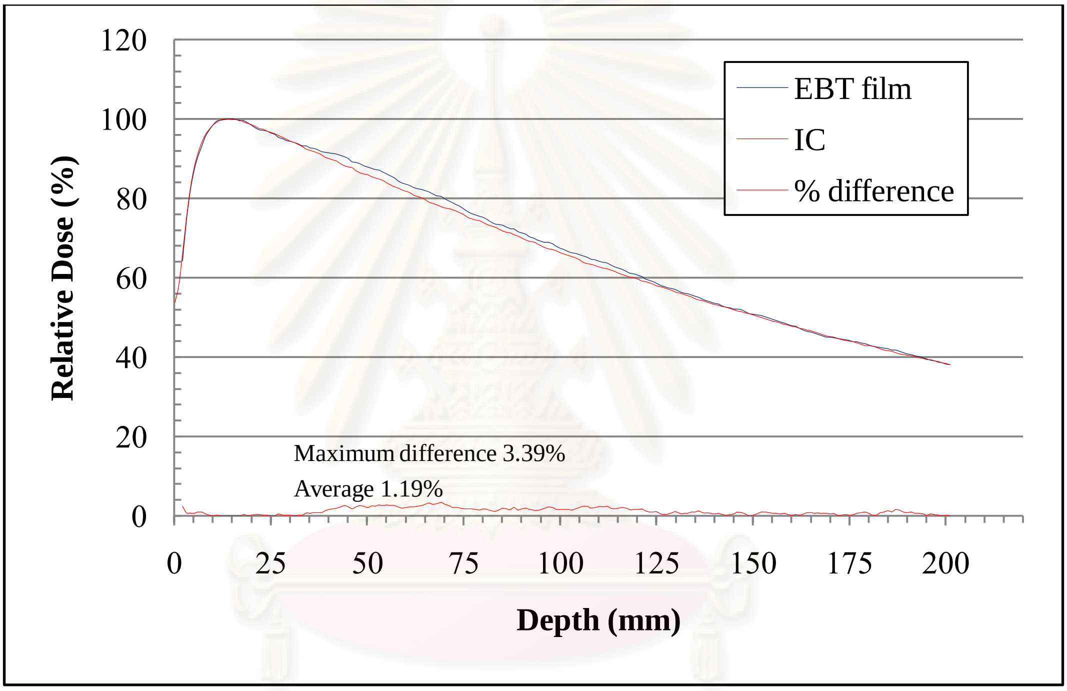


Figure 4.13 The comparison of percentage depth dose studied by Gafchromic™ EBT film and CC13 Ionization chamber for 10×10 cm^2 of field size.

The figure 4.14, 4.15 and 4.16 show comparison of beam profiles between CC13 ionization chamber and Gafchromic™ EBT film at 5 cm depth for 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2 field sizes, respectively.

The percentage relative dose of Gafchromic™ EBT film was normalized to central axis of beam. The beam profiles of EBT film and CC13 ionization were superimposed at central axis region but discrepancy at the high dose gradient and penumbra region. The EBT film gave sharper dose fall off than CC13 ionization chamber due to high resolution of film.

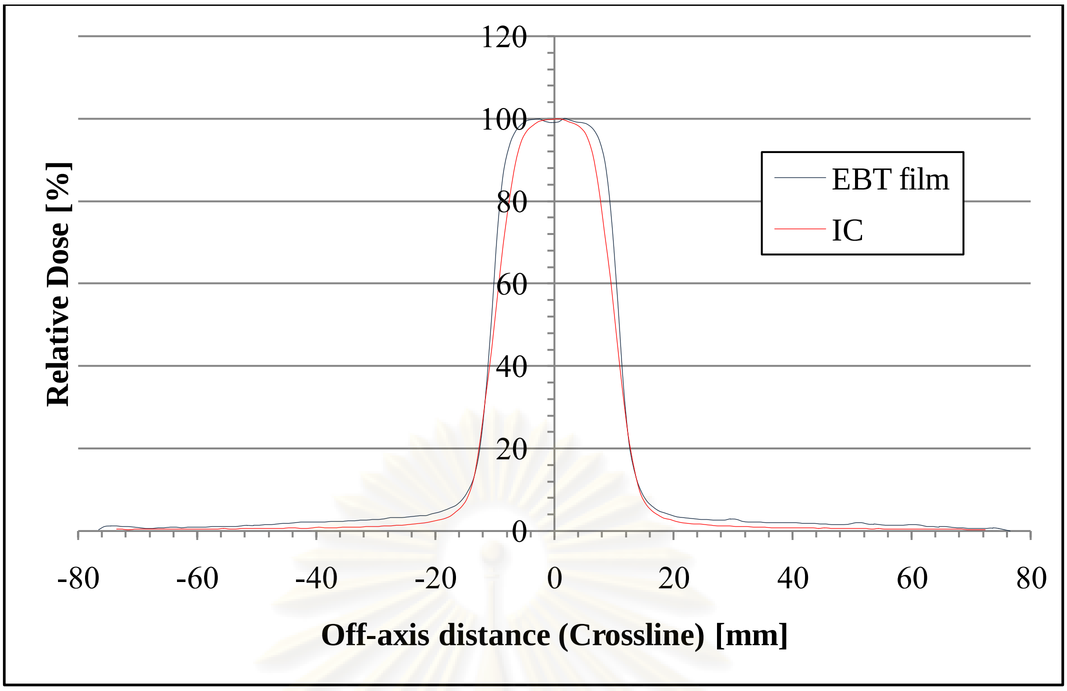


Figure 4.14 The comparison of beam profile obtained by Gafchromic™ EBT film and CC13 Ionization chamber for 2×2 cm^2 of field size at 5 cm of depth.

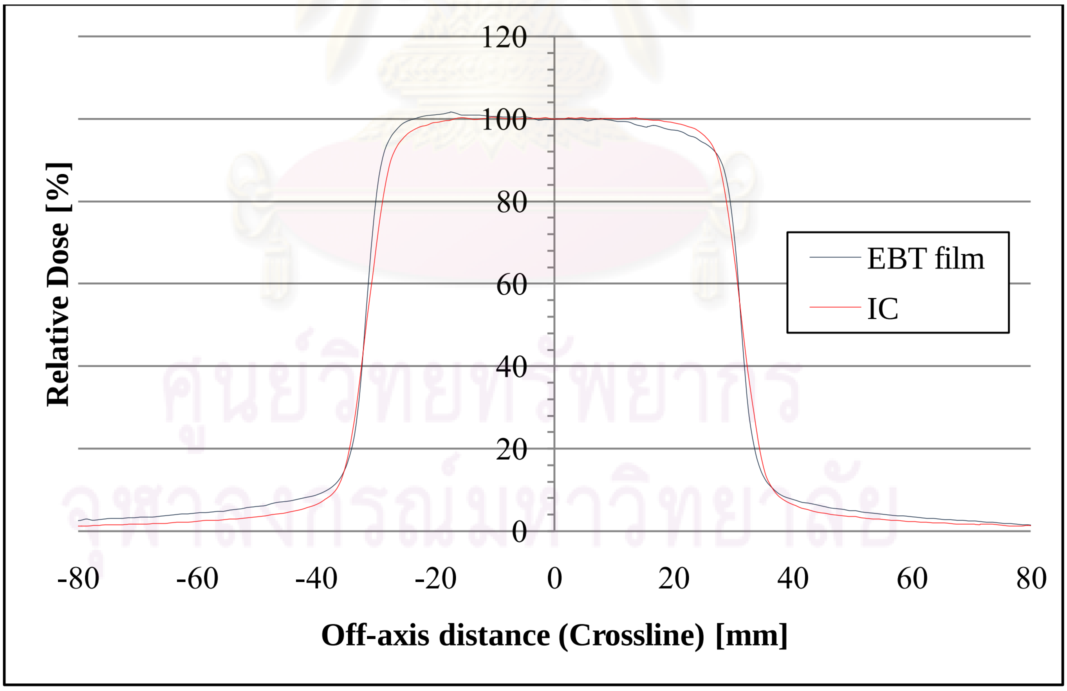


Figure 4.15 The comparison of beam profile obtained by Gafchromic™ EBT film and CC13 Ionization chamber for 6×6 cm^2 of field size at 5 cm of depth.

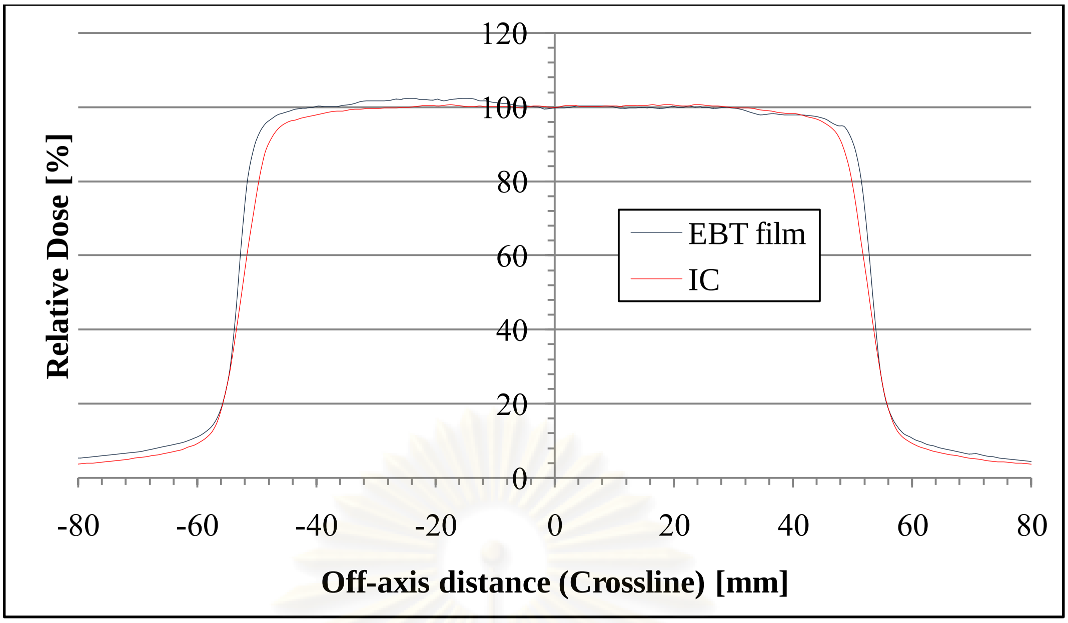


Figure 4.16 The comparison of beam profile obtained by Gafchromic^{TM} EBT film and CC13 Ionization chamber for 10×10 cm^2 of field size at 5 cm of depth.

4.5 Verification of clinical IMRT plan

The Gafchromic^{TM} EBT films were verified with three complex IMRT plans of two nasopharynx cancer and one brain tumor. The two sites of tumor were chosen due to more cases of treatment plans in our institute for 6 MV photon beams from Varian Clinac 21EX linear accelerator. The Gafchromic^{TM} EBT film was placed horizontal inside virtual water phantom at 5 cm depth with 20 cm of back scatter thickness. The composited beams were delivered at 0^0 gantry angle in order to simplify setup.

The two nasopharynx cancer and one brain tumor of composite IMRT plan were undertaken by Gafchromic^{TM} EBT film and then, compared with computed calculation plan which demonstrated in figure 4.17, 4.18 and 4.19 by (a) fluence map from Gafchromic^{TM} EBT film measurement, (b) fluence map from Eclipse treatment planning calculation, (c) gamma index and (d) beam profile comparison for case number 1, case number 2 and case number 3, respectively. The agreement of two methods dose distributions were evaluated with gamma index which the evaluation value should not be excess than 1 for percent dose different of 3% and 3 mm of distance to agreement. The red color sign in figure 4.17c, 4.18c and 4.19c was appeared when the values of EBT film measurement have been more than computed calculation and appeared blue color when the values of EBT film measurement have been less than computed calculation. The percentage passed of acceptable IMRT plan was 90%.

In this study, two IMRT plans of nasopharynx cancer were 82.5% and 90.6% passed for case number one and number two, respectively. The IMRT plan of brain tumor showed 97.8% passed. The values of percent fail were occurred at high dose gradient region due to the high spatial resolution of EBT film can detect dose distribution better than computed calculation.

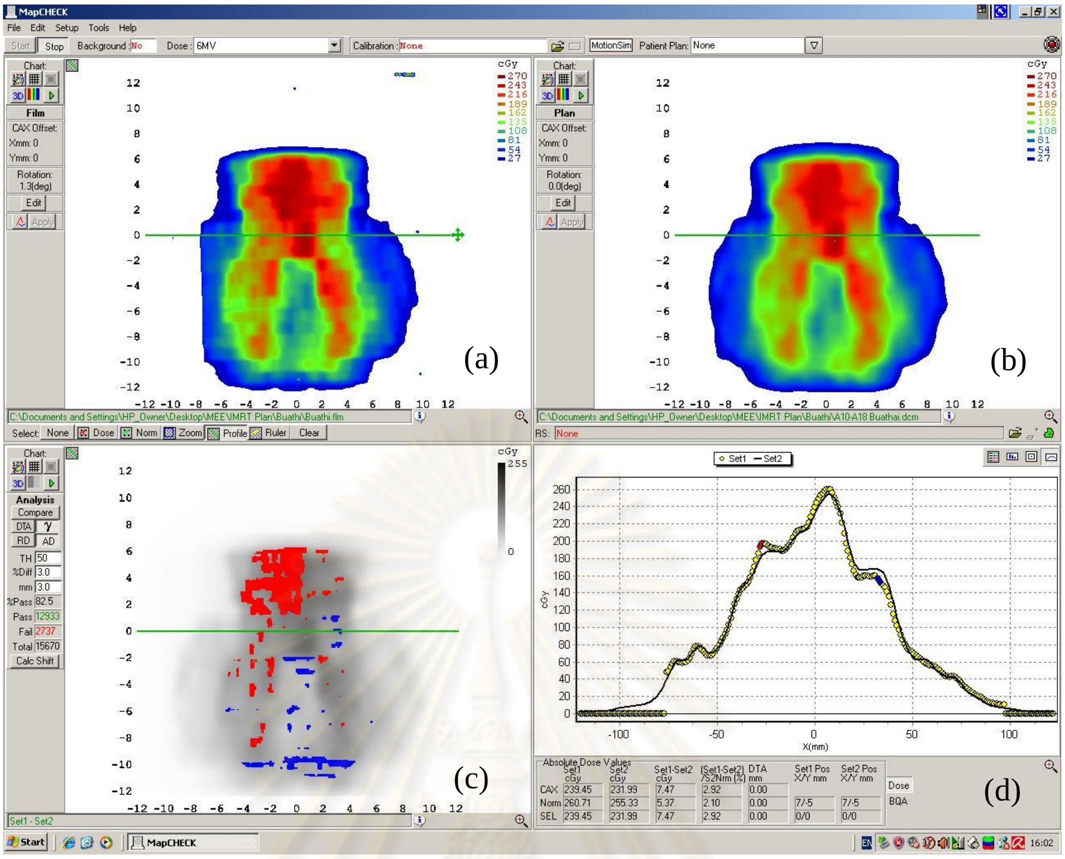


Figure 4.17 The verification of dose map between Eclipse treatment planning calculation and a Gafchromic^{TM} EBT film measurement of nasopharynx cancer case number 1, 9 beams composite plan for 6 MV photon beam.

(a) Fluence map from a Gafchromic^{TM} EBT film measurement
(b) Fluence map from Eclipse treatment planning calculation
(c) A comparison of fluence map in term of gamma index
(d) A comparison of beam profile

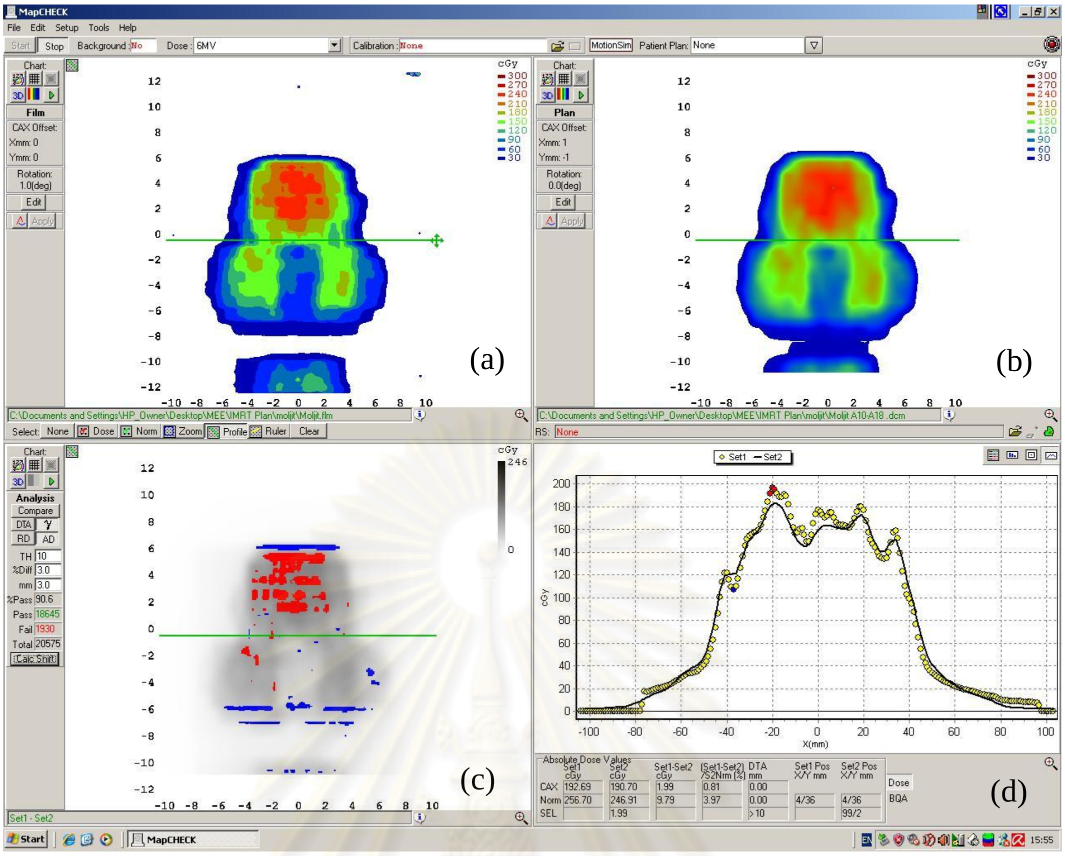


Figure 4.18 The verification of dose map between Eclipse treatment planning calculation and a Gafchromic^{TM} EBT film measurement of nasopharynx cancer case number 2, 9 beams composite plan for 6 MV photon beam.

(a) Fluence map from a Gafchromic^{TM} EBT film measurement
(b) Fluence map from Eclipse treatment planning calculation
(c) A comparison of fluence map in term of gamma index
(d) A comparison of beam profile

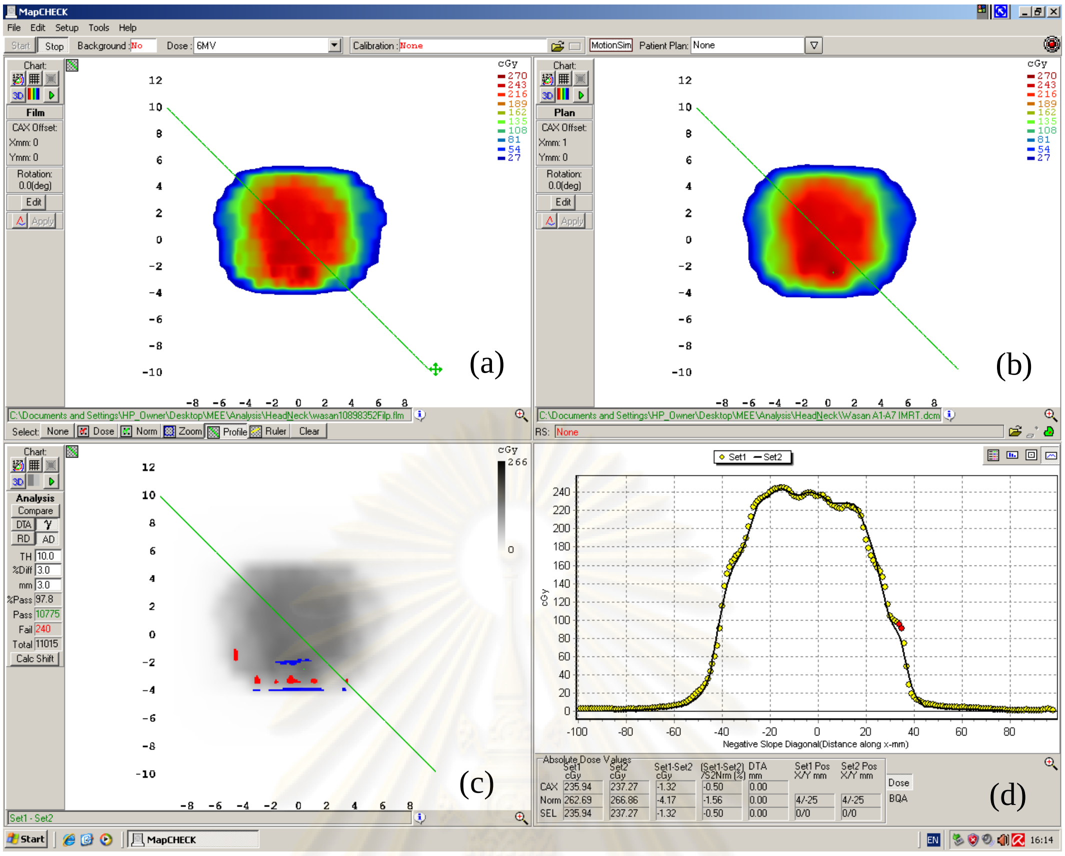


Figure 4.19 The verification of dose map between Eclipse treatment planning calculation and a Gafchromic^{TM} EBT film measurement of brain tumor case number 3, 7 beams composite plan for 6 MV photon beam.

(a) Fluence map from a Gafchromic^{TM} EBT film measurement
(b) Fluence map from Eclipse treatment planning calculation
(c) A comparison of fluence map in term of gamma index
(d) A comparison of beam profile

CHAPTER V

DISCUSSION AND CONCLUSION

5.1 Discussion

5.1.1 The characteristics of flat-bed color scanner

The factor-influence scanners response should be examined by response, repeatability, reproducibility and color band effect before studied a characteristics of Gafchromic^{TM} EBT film. The warm up of scanner was performed by preview scanning without a film at least 5 times before studied the characteristics of EBT film [18, 19] since the response of scanner was depending on the temperature stability.

The range of optical density that suitable for this scanner should not be more than 1.0. The repeatability of Epson Perfection V700 flatbed scanner was within 1.1% which quite agreed with Van Battum LJ et al. [16] who reported 0.5% for Epson 1680 Expression Pro transmission flatbed scanner.

The variation of reproducibility was within 1.0% for five days correspond to Van Battum LJ et al. [16] who found range of 0.3%-0.5%. Zeidan OA et al. [1] reported of 3% of scanner reproducibility using Microtek ScanMaker i900.

The red channel of a tagged image file format (TIFF) was highest sensitivity which agreed with several literatures [18, 19, 20, 21, 22].

5.1.2 The characteristics of Gafchromic^{TM} EBT film

The optimized stability of speed of film development was about 4 hours after irradiation which increasing 7%, after that it was increased about 1.7%. The speed of Gafchromic^{TM} EBT film development was varied with various doses which the lower dose presented more change of net optical density than higher dose. Our work agreed with Sankar A et al. [2] who found that the percent of density growth varied with the dose. The percentage of increasing density between 2 to 40 hours after irradiation was up to 7.33%. Zeidan OA et al. [6] showed that the optical density seem to stabilize about 100 mins. Rink A [20] reported that the optical density of film had increased roughly by 12.5%. Cheung T et al. [21] presented that the film produced a post-irradiation coloration effect of approximately 9%–11% which mostly occurred within the first 6 hours. So, for evaluation data in this study, we were waiting about 24 hours to assure the constant reading.

The polarization effect was more pronounced at low dose than high dose which the net optical density was changed up to 24% for the dose of 50 cGy. Zeidan OA et al.[1] reported that the direction of scan was very important because polarization effect will reduce signal up to 50%. Lynch BD et al. [22] reported that the polarization effect of Epson Expression 1680 scanner showed a 15% variation in OD over the range of angles for the 0 cGy film, it decreased to approximately 8% for the 300 cGy film. Their polarization effect was less than our study.

The non-uniformity of EBT film and Epson Perfection V700 scanner was about ±7% of 400 cGy which the far off-axis was presented effect more than nearly central axis. The effect of non-uniformity was occurred due to the light scatter of lamp scanner was interactive with active layer of EBT at central axis more than off-axis. Thus, the signal measurement at the area of central axis was higher than off-axis. This study agreed with Ferreira BC et al. [18] and Menegotti L et al. [14] who reported that the non-uniformity of EBT film and scanner were 6% and 9% for Epson Expression 10000XL and Epson Perfection V750, respectively. Lynch et al. [22] presented that a maximum variation of approximately 17% was observed for film profiles in the direction of the CCD array and approximately 7% in the direction orthogonal to the CCD array for the Epson Expression 1680 scanner.

The difference of output factor (field size factor) between EBT film and CC13 ionization measurement was within 2% for field sized of 2x2 cm^2 to 25x25 cm^2 which was higher than Van Battum L J et al. [16] who reported 0.2% of the variation of filed size factor from the ion chamber for field sized of 4x4 cm^2 to 30x30 cm^2.

The dose rate range of 208.33 cGy/min to 468.75 cGy/min was shown variation of 0.3% for real time measurement which corresponding to Rink A et al. [17] who found the dose rate effect about 1% for real time measurement.

The repeatability rate range of 100 MU/min to 600 MU/min was shown variation within 0.4% after 24 hours measurement. Thus, the dose rate and repeatability rate effect were not affecting to the characteristics of Gafchromic^{TM} EBT film.

5.1.3 The sensitometric curve of Gafchromic^{TM} EBT film

The sensitometric curve shows as a third-order polynomial fitted curve. The Gafchromic^{TM} EBT film revealed the narrow net optical density range of 0.00 to 0.42 for dose 0 cGy to 400 cGy, contrast to Sankar A et al. [2] who reported OD range of 0.42-1.02. In this study, the suitable dose range of EBT film should not be greater than 400 cGy. Sankar A et al. [2] suggested three methods for the accuracy of dose measurements because of differential density growth.

1) Applying appropriate growth correction factors for individual doses.
2) Maintaining the same time difference between the film irradiation and scanning for both calibration and experimental films.
3) Creating a number of calibration data sets by scanning the calibration films at difference times after irradiation, so that an appropriate calibration data set can be used depending on the scanning of experimental film after irradiation.

5.1.4 Percentage depth dose and beam profile

The average differences of percentage depth dose between Gafchromic^{TM} EBT film and CC13 ionization chamber were 3.11%, 0.64% and 1.12% for 2×2 cm^2, 6×6 cm^2 and 10×10 cm^2 field size at 5 cm depth, respectively. The maximum difference was about 4% which showed at the region of large depth. This study, agreed with Van Battum L J et al. [16] found that the average difference between ionization chamber measurement and EBT film was 1.0% (1SD), with maximum difference up to 3% for 10×10 cm^2 field size of 6 MV photon beam. Schneider F. et al. [15] reported that the comparison of the film depth dose curve showed a relative pixel to pixel deviation±standard deviation of 1.15%±0.76% and a maximum deviation of 3.1% for 5×5 cm^2 field size.

The discrepancy of beam profile between Gafchromic™ EBT film and CC13 ionization chamber was presented at region of off-axis and high dose gradient which agreed with Van Battum L J et al. [16].

5.1.5 Verification of clinical IMRT plan

Before using Gafchromic™ EBT film for IMRT verification, the correction of non-uniformity should be corrected in the MapCheck software. The agreement of the dose distributions between calculated and measured were evaluated with gamma index which the evaluation value should not be excess more than 1 for percent dose different of 3% and 3 mm of distance. Thus, the gamma index (γ < 1) can be considered to fall within tolerance and to be acceptable with regard to the reference dose distribution.

The criterion of verification of treatment planning system (TPS) and EBT film measurement was 90% passed which found that the one nasopharynx and brain tumor cancer plan were passed. The EBT film was shown to produce acceptable agreements between calculated and measured dose distributions by analyzing IMRT plans of acceptance criteria of the gamma index [13].

5.2 Conclusion

The characteristics of scanner should be studied by relation of net optical and pixel value, repeatability reproducibility and color band, before examined the characteristics of Gafchromic™ EBT film. The preview scanning was performed at least five times for temperature stability. The characteristics of film such as speed of film development, polarization effect and uniformity were very important because of the stability time of net optical density and the direction of non-polarization effect should be selected. The uniformity of film was affected to dose distribution verification, it needed to be corrected before scanning. The percentage depth doses and beam profiles of EBT film measurement were comparable to CC13 ionization chamber measurement.

Finally, The Gafchromic™ EBT film did not require processing film which can reduce effect of net optical density changed. The Gafchromic™ EBT film can be implemented as a dosimetric verification of advanced radiation treatment techniques.

5.3 Recommendation

The temperature stability of scanner is important for data analysis which preview scanning should be scanned at least five times. This study, agreed with Paelinck L et al. [19] who reported that the optical density resulting from the first scan is unreliable due to warm-up effects. Therefore, each film is consecutively scanned five times and the optical density of the last three scans was averaged.

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