

**COMPARATIVE PENUMBRAL WIDTHS FOR SMALL  
FIELDS OF 6 MV PHOTON BEAM**



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Thesis  
entitled  
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OF 6 MV PHOTON BEAM**

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(MEDICAL RADIATION PHYSICS), LALIDA TUNTIPUMIAMORN, M.Sc.  
(RADIOLOGICAL SCIENCE)****ABSTRACT**

The aim of this study is to evaluate the Photon diode detector (PFD), EDGE detector, and Stereotactic diode detector (SFD) used to measurement the penumbral width by means of comparing radiographic (EDR2) and radiochromic (EBT2) films in small fields of 6 MV photon beams.

Penumbral widths for field size of  $1 \times 1$ ,  $2 \times 2$ , and  $3 \times 3$  cm<sup>2</sup> at depths of 1.5, 10, and 20 cm were measured using PFD, EDGE, and SFD diodes. The OmniPro-Accept 7.2 software with scanning step distance of 0.5 mm was employed. Films (EDR2 and EBT2) were used as a reference penumbral width measurement for comparison. A Vidar scanner and the ImageJ software were used for film scanning analysis at resolution of 0.36 mm/pixel (71 DPI). The film calibration curves were fitted using a polynomial equation of degree 2.

The minimum and maximum penumbral widths measured of EDR2 were  $2.24 \pm 0.05$  mm and  $3.35 \pm 0.36$  mm. The minimum and maximum penumbral widths measured of EBT2 were  $2.19 \pm 0.07$  mm and  $3.09 \pm 0.30$  mm. It was found that there was no significant difference between EDR2 and EBT2 film for all experimental field sizes and depths. The minimum and maximum penumbral widths measured by PFD, EDGE, and SFD were 2.3-3.33 mm, 2-3.2 mm, and 1.9-3.05 mm, respectively. Comparison between EBT2 films and diodes, penumbral widths measured by PFD had the widest penumbral width. EDGE obtains comparable penumbral width. The penumbral widths measured by SFD had the distinctly smallest penumbral width.

The EDR2 has slightly energy dependence compared with EBT2 film. It obtained wider penumbral width than EBT2, however, there is no significant difference between them. The penumbral width measured from various diode detectors shares close similarity with both EDR2 radiographic and EBT2 radiochromic film. Over all, the results found that they are different within  $\pm 0.5$  mm.

**KEY WORDS: SMALL FIELD / PENUMBRAL WIDTH / EDGE DETECTOR /  
PHOTON DIODE DETECTOR/STEREOTACTIC DIODE DETECTOR**

65 pages

การเปรียบเทียบขนาดขอบพื้นที่รังสีสำหรับพื้นที่ขนาดเล็กของลำรังสีโฟตอนพลังงาน 6MV  
COMPARATIVE PENUMBRAL WIDTHS FOR SMALL FIELDS OF 6 MV PHOTON BEAM

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บทคัดย่อ

วัตถุประสงค์ของงานวิจัยนี้คือเพื่อศึกษาความถูกต้องของ Photon diode detector, Edge detector และ Stereotactic diode detector ในการวัดบริเวณขอบพื้นที่รังสีโดยเปรียบเทียบกับ radiographic (EDR2) และ radiochromic (EBT2) ในพื้นที่ขนาดเล็กของลำรังสีโฟตอนพลังงาน 6 MV

วัดข้อมูล บริเวณขอบพื้นที่รังสี ของพื้นที่ขนาด 1x1 ถึง 3x3 ตารางเซนติเมตรที่ความลึก 1.5, 10 และ 20 เซนติเมตร โดย PFD, EDGE และ SFD ซึ่งใช้ OmniPro-Accept 7.2 ในการเก็บข้อมูลระยะ ความห่างของแต่ละข้อมูลเป็น 0.5 มิลลิเมตรฟิล์ม EDR2 และ EBT2 ใช้เป็นตัวอ้างอิงในการเปรียบเทียบบริเวณขอบพื้นที่รังสี Vidar scanner และ imageJ software ใช้ในการประมวลผลด้วยความละเอียด 0.36 มิลลิเมตรต่อพิกเซลและ ใช้สมการ polynomial กำลังสองในการสร้าง calibration curves ของฟิล์ม

ค่าต่ำสุดและสูงสุดของบริเวณขอบพื้นที่รังสีที่วัดด้วย EDR2 คือ  $2.24 \pm 0.05$  มิลลิเมตร และ  $3.35 \pm 0.36$  มิลลิเมตร ค่าต่ำสุดและสูงสุดของบริเวณขอบพื้นที่รังสีที่วัดด้วย EBT2 คือ  $2.19 \pm 0.07$  มิลลิเมตร และ  $3.09 \pm 0.30$  มิลลิเมตร ซึ่งพบว่าไม่มีความแตกต่างกันอย่างมีนัยสำคัญระหว่าง EDR2 และ EBT2 ของพื้นที่และความลึกต่าง ๆ ค่าต่ำสุดและสูงสุดที่วัดโดย PFD, EDGE และ SFD คือ 2.3-3.33 มิลลิเมตร , 2-3.2 มิลลิเมตร และ 1.9-3.05 มิลลิเมตรตามลำดับเมื่อเปรียบเทียบระหว่าง ฟิล์ม EBT2 กับ ไดโอด พบว่าบริเวณขอบพื้นที่รังสีที่วัดด้วย PFD จะมีขนาดใหญ่ที่สุด EDGE วัดขอบพื้นที่รังสี ที่ได้ไม่มากที่สุดหรือน้อยสุด SFD วัดบริเวณขอบพื้นที่รังสีได้น้อยที่สุด

ค่าความกว้างของขอบลำรังสีวัดโดย EDR2 ขึ้นอยู่กับพลังงานมากกว่าเมื่อเปรียบเทียบกับ EBT2 โดยขนาดของบริเวณขอบพื้นที่รังสีจะกว้างกว่า EBT2 แต่อย่างไรก็ตามไม่มีความแตกต่างกันอย่างมีนัยสำคัญระหว่างฟิล์มทั้งสอง ชนิด บริเวณขอบพื้นที่รังสี ที่ได้จากการวัดด้วย ไดโอดพบว่ามีความใกล้เคียงกันเมื่อเปรียบเทียบกับฟิล์ม EDR2 และ EBT2 ซึ่งผลของการวัดมีความแตกต่างกันอยู่ภายใน  $\pm 0.5$  mm

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## LIST OF ABBREVIATIONS

<b>Abbreviation</b>	<b>Term</b>
cGy	Centigray
cm	Centimeter
cm <sup>2</sup>	Square centimeter
cm <sup>3</sup>	Cubic centimeter
CPE	Charged particle equilibrium
d	Depth
d <sub>max</sub>	Depth of maximum dose
IC	Ionization chamber
IMRT	Intensity Modulated Radiation Therapy
mm	Millimeter
mm <sup>3</sup>	Cubic millimeter
MLC	Multileaf collimator
MU	Monitor Unit
MV	Megavolt
OAR	Off-axis ratio
OD	Optical Density
PDD	Percent depth dose
PFD	Photon diode detector
S <sub>cp</sub>	Total scatter factor
SD	Standard Deviation
SFD	Stereotactic diode detector
SRS	Stereotactic. Radiosurgery
SSD	Source to surface distance
TMR	Tissue maximum ratio
TPS	Treatment planning system

## CHAPTER I

### INTRODUCTION

Cancer patients treated by conventional radiation employ the size of the radiation beam from  $4 \times 4$  to  $40 \times 40$  cm<sup>2</sup>. However advanced radiation therapy has been developed which helps to reduce the size of the beam less than  $4 \times 4$  cm<sup>2</sup> such as Intensity Modulated Radiation Therapy (IMRT), Tomotherapy, Stereotactic Radiosurgery (SRS), Gamma Knife and Cyber Knife. IMRT is commonly used in the treatment of many cancer sites such as prostate and head and neck. The concept of IMRT achieves in reducing damage to normal tissues while increasing dose to tumors. This has the potential to improve local control of the tumor and reduce side effects to normal organs. The technique changes the intensity of the beam by dynamic movement of multileaf collimator (MLC). A beam is divided into small segments and each of the segments comprises many small beamlets providing different radiation intensities. The intensity of this nature will cause steep dose gradient.

The main issues of small segment fields especially at the penumbral regions are electronic disequilibrium and steep dose gradient. Therefore the accuracy of the measurements in the penumbral region especially in the IMRT technique is a fairly challenging. First of all, Das et al.[1] tried to define the problems of small field dosimetry and pointed that when the beam is small, it causes lacking of CPE because the beam size is smaller than the range of secondary electrons which depends on the energy and density of the medium. However the field size less than  $3 \times 3$  cm<sup>2</sup> is usually considered a small field. In the clinical situation, Mark R. Arnfield et al[2]. found that inaccurate dose calculation for IMRT technique by treatment planning system might occur when using a finite detector size for penumbra measurement. However there are various types of small detectors recommended by many publications to deal with penumbral width in small beam measurement.

M Heydarian et al [3]. found that the penumbral width using a Scanditronix p-type photon silicon diode overestimate comparing with that of Monte

Carlo technique and diamond detector because its large sensitive volume dominates. The penumbra measured with XV-film dosimetry was wider than other detectors because there were the energy dependence problem and the loss of high resolution from film scanners. The Monte Carlo technique and diamond detector were appropriate detectors for regions with the lack of lateral electronic equilibrium. This finding agreed with Bucciolini et al[4]. who reported that Diamond detector is quite suitable for small field and steep dose gradient due to tissue equivalence but it is suffered from dose rate dependence and great expense. Tsang Cheung et al[5]. also reported that the X-Omat V was not suitable to measure penumbral width because of the large energy dependence. The Kodak EDR2 and the Gafchromic<sup>TM</sup>EBT were more suitable detector for penumbral width measurement but EBT had superior property than EDR2 due to its near- tissue equivalence and self-developing. However the authors performed for large field sizes between  $5 \times 5$  and  $30 \times 30$  cm<sup>2</sup>.

M Westermark et al[6]. pointed out that the penumbral width for diameter of photon beams  $\geq 4$  mm measured with a liquid ionization chamber and a plastic scintillator were slightly broadened due to their finite size. The measured with a double diode (designed to reduce a directional dependence) obtained smaller penumbral width due to its smaller size and higher density material.

Lárraga-Gutiérrez M. José et al[7]. accepted SFD diode as a standard measurement for narrow photon beams to evaluate EBT2 radiochromic film. They found that the film could be considered competent for measuring penumbral width but it still has somewhat inherent energy dependence.

In brief summary, CC01, Scanditronix p-type photon silicon diode and RK chamber are not suitable detector because they have volume-averaging effects which lead to overestimate penumbra width. The liquid ionization chamber and a plastic scintillator are slightly broadened due to the finite size. Moreover, the Kodak XV film has large energy dependence and also film scanner effect. The diamond detector has dose rate dependence and great expense.

EDGE detector is a new device that is designed for small fields in the scanning beam measurement. It is a diode encapsulated in a rectangular housing made of thin brass sheet. Its active dimension is 0.8 mm. It is intended to use for small field beam data collection modeling for intensity modulated radiation technique.

Therefore this study will evaluate the new designed diode called EDGE detector for penumbral width measurement at small field sizes (defined only by jaws). The stereotactic diode detector (SFD) is one of the diode detectors constructed for small field measurement due to its high resolution and high sensitivity therefore it will also be assessed to compare with the EDGE detector. The photon diode detector (PFD) was clearly not suitable for penumbral width measurement in small field (M Heydarian et al[3] therefore it will be employed to demonstrate as a poor result. The EDR2 radiographic film and EBT2 radiochromic film will be served as a reference for comparison.

## **CHAPTER II**

### **OBJECTIVE**

The objective of this study is :

1. To evaluate various diode detectors in measurement of penumbral width by comparison with radiographic and radiochromic film for small fields of 6 MV photon beams.

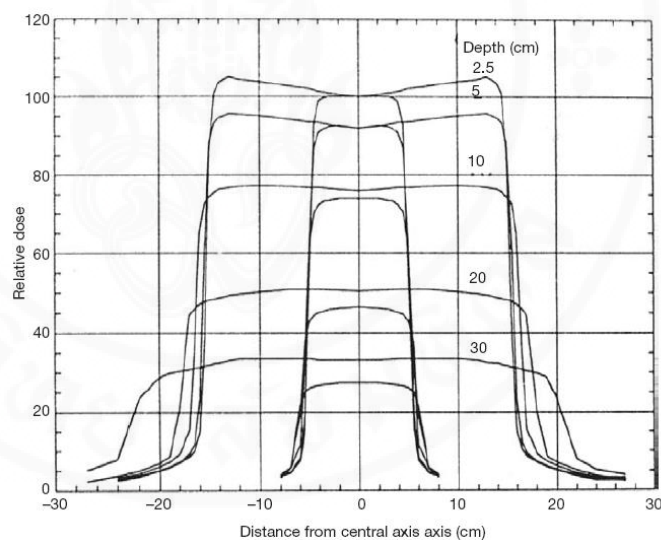
## CHAPTER III

### LITERATURE REVIEWS

#### Basic knowledge

##### Beam Profile [28]

The off-axis data are given with beam profiles measured perpendicularly to the beam central axis at a given depth in a phantom is composed of three parts: the Central region, Penumbra region and Umbra region.



**Figure 3.1** Central region , Penumbra region and Umbra region

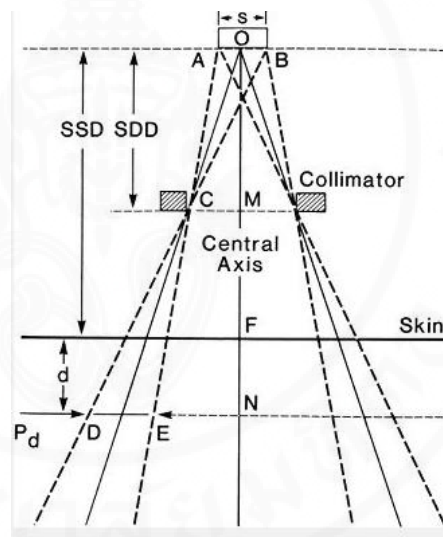
Central region is the central portion of the profile extending from the beam central axis to within 1-1.5 cm. from the geometric field edges of the beam. For the Central region of the accelerator beam profile depends on the energy of the electrons collide with the target, the target atomic number, atomic number of the flattening filter and the shape of the flattening filter.

Penumbra region is the dose changes rapidly and the dose falloff around the geometric beam edge is sigmoid in shape and extends under the collimator jaws into the penumbral tail region(20-80% or10-90%).

Umbra region is the region outside the radiation field, far removed from the field edges and the dose in this region is generally low and results from radiation transmitted through the collimator and head shielding.

Physical Penumbra consists of three parts.

1. Transmission penumbra is penumbra of the radiation transmitted through the edge of collimator jaw.
2. Scatter penumbra is penumbra caused by the scattering of x-rays in matter.
3. Geometric penumbra is penumbra caused by the influence of source size, SDD and the depth of the medium.



**Figure 3.2** Diagram for calculating geometric penumbra

The Geometric penumbra ( $P_d$ ) at a depth ( $d$ ) of the skin of the patient can be determined from similar triangles  $ABC$  and  $DEC$  which the equation.

$$\frac{DE}{AB} = \frac{CE}{CA} = \frac{CD}{CB} = \frac{MN}{OM} = \frac{OF + FN - OM}{OM} \quad (1)$$

$AB = s$  ( the source diameter)

$OM = SDD$ (the source to diaphragm distance)

$OF = SSD$ (the source to surface distance)

From the equation (1) can determine the Geometric penumbra (Pd) at different depths from the equation.

$$Pd = \frac{s(SSD + d - SDD)}{SDD} \quad (2)$$

The Geometric penumbra (Pd) at the surface can be calculated by substituting  $d = 0$ , and the relation of equation (2) Geometric penumbra (Pd) will increase if the increase of the source size, SSD and. deep in the medium and Geometric penumbra (Pd) is reduced when adding the SDD.

Factors contributing to the increase in the width of the Penumbra are

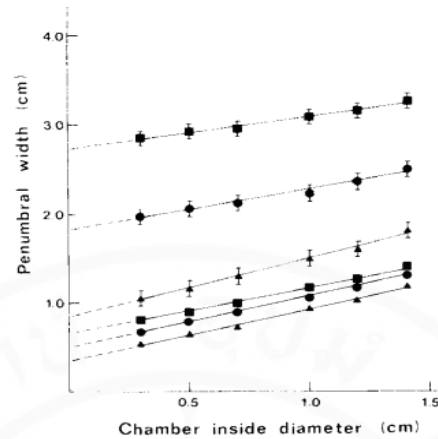
- The flattening filter. Because it makes the size of the focal spot wider.
- Increasing depths. Because when the depth increases, the scattering of photons increases.
- Energy photon  $> 10\text{MV}$ . Because secondary electrons are scattered far and without compensation to the edge of the beam.

At present, new techniques use in the treatment of cancer patients in radiation therapy has been developed with the use of a small beam treatment. Therefore, the accuracy and precision of penumbral regions in small field dosimetry are significance because the treatment planning uses this information to calculate the dose.

However, the measurement of penumbra is complicated because it presents the effects of electronic disequilibrium and steep dose gradient.

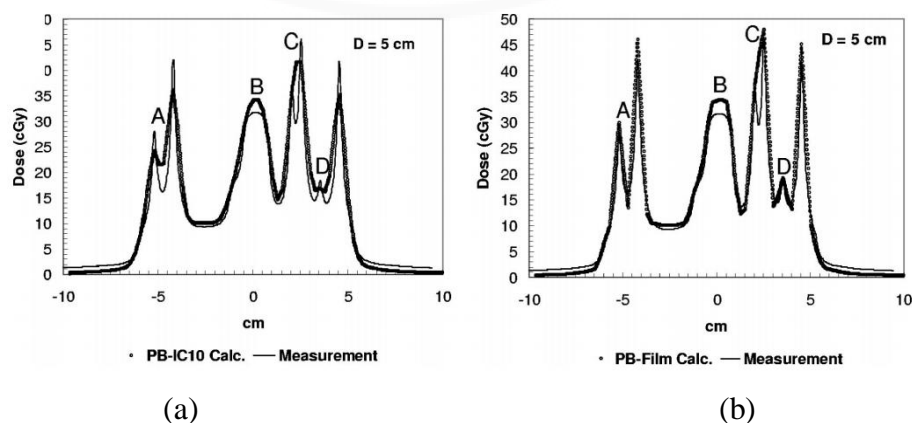
There were many publications notified that different sizes of detectors causing different sizes of penumbral widths which directly affect the accuracy of treatment planning calculation.

Dawson DJ. et al[8]. studied penumbra measurement using various ionization chamber sizes with a diameter from 0.3 to 1.4 cm at 2.5 to 25 cm depth of Co60, 6 and 31 MV photon beams. The results presented that penumbral widths between 20-80% dose ( $P_{20-80}$ ) and 10-90% dose ( $P_{10-90}$ ) increased linearly when diameters of ionization chambers increased at any depths and energies as shown in Figure 3.3



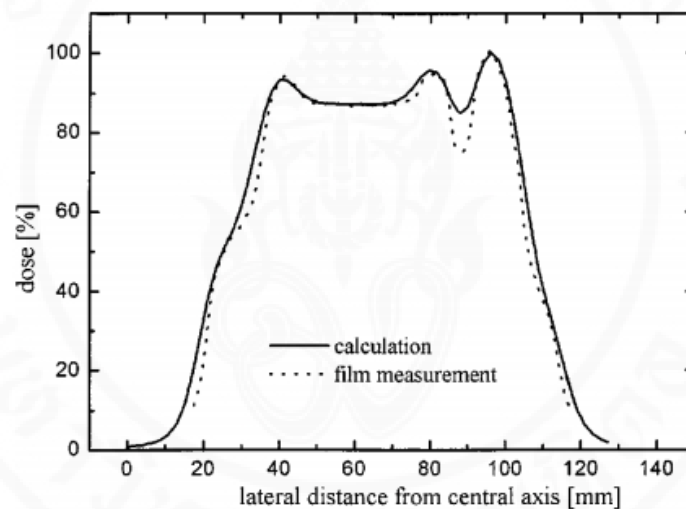
**Figure 3.3** Penumbral widths increased linearly with chamber diameters. The first three lines represent  $P$  10-90 and the last three lines illustrate  $P$  20-80 at depths of 5, 15, and 25 cm for 6 MV photon beams.

Mark R. Arnfield et al[2]. studied the accuracy of the calculation in IMRT techniques which contain many small fields of Varian Eclipse planning by improving the commissioning beam data at the penumbral region using higher spatial resolution such as film dosimeter for measurement. They compared the result of IMRT fields between the original beam data set collected by IC-10 chamber and those measured by Kodak XV-2 film and found that the latter can achieve better accuracy of IMRT dose calculation by 18-20% especially at high dose gradient, except peak B and C, as shown in Figure 3.2. Therefore, the accuracy of the measured penumbral width was essential in order to ensure the accuracy of treatment planning calculation.



**Figure 3.4** Profiles IMRT comparison at depth 5 cm in phantom using Kodak XV-2 film for a reference comparison, (a) Profiles calculated by the beam data set of penumbral regions measured with IC10 chamber and (b) those measured with Kodak XV-2 film

Wolfram U. Laub et al[9]. studied the effect of detector sizes in the commissioning beam data for using in IMRT technique. The cross profiles of prostate IMRT technique were compared between the measurement by Kodak EDR 2 film and the calculation by Pinnacle treatment planning system (TPS) in which the 0.125 cm<sup>3</sup> ionization chamber was used for the commissioning of that TPS. Figure 3.3. shows that the calculated dose was overestimated by 10% compared with the measured one. The reason for that is because the ionization chamber suffers from the volume averaging effect.



**Figure 3.5** Comparison of cross profiles between calculated by Pinnacle TPS and Kodak EDR 2 film measurement.

Researches by Arnfield and Laub et al[2,9] showed that when the data were collected using detector with coarse spatial resolution, it could lead to the erroneous calculations of computer treatment planning system. So it is crucial importance to select the suitable detector for beam data collection of IMRT technique.

### **Penumbral width measurement by film**

Tsang Cheung et al [5]. studied the Gafchromic<sup>TM</sup>EBT film to measure the penumbra region of high energy of 6 MV photon beams by measuring at depth of 0.12, 1.5, 5 and 10 cm for field size of 5×5 to 30×30 cm<sup>2</sup>. The results were compared with Kodak EDR 2 and Kodak X-Omat V films. The extrapolation method among various sizes of ionization chambers was used for measuring reference penumbral widths. The penumbra widths using X-Omat V radiographic film had the largest values compared with other detectors due to its large energy dependence. The penumbra width measured with Kodak EDR 2 and the Gafchromic<sup>TM</sup>EBT film were closely to the values obtained from the extrapolation method so the Kodak EDR 2 and the Gafchromic<sup>TM</sup>EBT were adequate dosimetry for penumbra measurement. However, Kodak EDR 2 had disadvantages such as energy dependence at low energy photon and film processor required which the Gafchromic<sup>TM</sup>EBT was superior to the Kodak EDR 2 for example near- tissue equivalence, less energy dependence as well as self-developing film.

### **Penumbral width measurement by various diode detectors**

Beddar et al [10]. studied the effect of scanning direction and the structure of diode for beam profile measurement for 1, 2 and 3 cm circular cone diameter of Stereotactic radiosurgery 6 MV photon beams using a p-type Si photon diode (PFD), and a p-type Si electron diode (EFD). In this study, there are three scanning directions for measurement. For the direction one, the diodes were set parallel with the central axis and perpendicular to the scan direction. For the direction two and three, the diodes were set perpendicular with the central axis and parallel to the scan direction but scanned in an opposite direction. The result presented that beam profiles from direction one using both diodes were symmetry profiles for all field sizes and beam profiles from direction two and three using both diode were not symmetry profiles for all field sizes. Because all parts of diodes faced to the radiation equally between left and right half profiles, that made the direction one's beam profile symmetry. However, according to the direction two and three, less part of diodes faced to the radiation at one half beam profile and most part of diodes faced to the radiation at the other half

beam profile, those created asymmetry of beam profiles. As expected, all field sizes, the penumbral width from direction two and three were less than that of the direction one because the amount of the detector's size faced to the radiation of direction two and three were less than that of the direction one. They commented further that there was not only the diode's size affected to the penumbral width but also the material of the diode. Because its material was made of higher density compared to water, the secondary electron range was shorter, forming less penumbral width .

Kyung-Hwan Chang et al [11]. studied the EDGE detector to measure in small field dosimetry which there were beam profile measurement using EDGE detector compared with a standard volume ionization chamber(CC13) and photon diode detector(PFD) for square field size  $1 \times 1, 2 \times 2, 4 \times 4, 6 \times 6, 8 \times 8$  and  $10 \times 10$  cm<sup>2</sup> at depth 0.5, 1.5, 5, 10, 20 and 30 cm of 6 MV photon beam. The penumbra widths(10-90% and 20-80%) were analyzed to discuss result. The result presented that the penumbra measured were depend on the sensitive volume and type of detector. The penumbra widths(20-80%) and penumbra widths(10-90%) measured with EDGE detector were narrower than measured from using ionization chamber(CC13) and photon diode detector(PFD) for all field size. In this study, Inaccuracy of measurement of the penumbra due to volume averaging effect for small field size and the EDGE detector more appropriate than other detector for small field. Therefore, the EDGE detector was suitable detector for quality assurance(QA) and commissioning of small field dosimetry .

### **Penumbral width compared between films and diode detectors measurement**

M Heydarian et al[3]. studied comparison of off axis factors (OAFs) measurement between a PTW Riga diamond detector, a Scanditronix p-type photon silicon diode, X-Omat V Kodak film and Monte Carlo techniques for 7 and 23 mm SRS collimator. The result showed that the penumbral width using diode were wider than penumbra measurement by diamond detector and Monte Carlo techniques due to there was large sensitive volume. The penumbral width using film dosimetry were

wider than the other detector due to there were energy dependent and also effect from film scanning. The results of this experiment showed that in the lack of lateral electronic equilibrium to made measurements of the detector is not valid and will increase as a result of tissue nonequivalence and detector size increase. Monte Carlo techniques was qualify reference for SRS where the lack of lateral electronic equilibrium. The penumbra width measurement with diamond detector agreed with Monte Carlo techniques so diamond detector was potential detector for SRS .

Jose M. Larraga-Gutierrez et al[7]. studied the comparison of off-axis ratio measurement between Gafchromic EBT2 film and Stereotactic field diode (SFD) of Novalis linear accelerator with 6MV photon beam for circular collimator diameter 4,6,7.5,10,12.5,15,17.5 and 20mm. They reported that the penumbra width from Gafchromic EBT2 film measurement were larger than SFD diode measurement for all circular collimator diameters as shown in Table 3.1 because Gafchromic EBT2 film had energy dependent and blurring effect of scanner system could increase the penumbral width. However, the different of penumbral width of Gafchromic EBT2 film and SFD diode were less than the grid resolution used for treatment planning calculation. Table 3.1 presents the penumbral width measured by SFD. The differences were compared to the EBT2 film with p-value for the statistical analysis.

**Table 3.1** The differences penumbral width measured by SFD and EBT2 film with p-value for the statistical analysis

Diameter [mm]	Penumbra 80%–20% [mm]	Difference [mm]	<i>p</i>
4	1.35	−0.06	0.007
6	1.47	−0.11	0.013
7.5	1.56	−0.15	0.006
10	1.71	−0.17	0.006
12.5	1.81	−0.29	0.006
15	1.85	−0.26	0.006
17.5	1.86	−0.32	0.006
20	1.93	−0.25	0.006

## CHAPTER IV

### MATERIALS AND METHODS

#### 4.1 MATERIALS

##### 4.1.1 Linear accelerator

Figure 4.1 shows the ClinaciX linear accelerator used in the experiment and it is manufactured by Varian Oncology Systems, Palo Alto, CA, with dual photon beam energies of 6 MV and 15 MV and six electron beam energies of 4, 6, 9, 12, 16, and 20 MeV. The photon field size ranges from  $0.3 \times 0.3 \text{ cm}^2$  to  $40 \times 40 \text{ cm}^2$  at the isocenter. The distance from the target to isocenter is 100 cm. There are five stationary therapy dose rate ranges from 100-600 monitor units per minute. The MLC has the maximum number of 120 tungsten MLC leaves which mounted below the conventional collimator in the same direction of X-jaws[12].



Figure 4.1 The ClinaciX linear accelerator

#### 4.1.2 Water phantom

Figure 4.2 shows the Bluephantom<sup>2</sup> (ScanditronixWellhoferDosimetric, Schwarzenbruc, Germany) which made from acrylic plastic (Perspex), having the scanning volume of 48×48×41 cm<sup>3</sup>. It is programmed by the OmniPro-Accept 7.2 Software (IBA Advanced Radiotherapy, ScanditronixWellhofer,Uppsala,Sweden). This phantom can be used for scanning percentage depth dose, beam profile and penumbra measurement with a variety of detectors. The blue phantom is a device which is used to collect and analyze beam data of Linear accelerator. It consists of a three – dimensional servo (the Blue phantom tank with mechanics), a control unit with two channel electrometer (CU500E) and two single detectors (ionization chamber). The system can be used in air measurements. Moreover, the semiconductor detectors, cylindrical and plane parallel ionization chamber can be used with the BluePhantom<sup>2</sup> system. The OmniPro-Accept is a software which is used to analyze and measure dose distribution for quality assurance, calibration of radiation devices, collect input data to Treatment Planning System and acceptance testing[13].



Figure 4.2 The Blue Phantom<sup>2</sup> (ScanditronixWellhoferDosimetric, Schwarzenbruc, Germany)

#### 4.1.3 Solid water phantom

Figure 4.3 shows the solid water phantom made in square slab of  $30 \times 30 \times 30 \text{ cm}^3$  with the thickness of 0.5, 1.5 and 5 cm manufactured by RMI. It has electron density of  $1.030 \text{ g cm}^{-3}$  [14].



Figure 4.3 RMI solid water phantoms

#### 4.1.4 EDGE™ detector

EDGE™ detector of Sun Nuclear corporation shown in Figure 4.4 consists of brass housing wall. The detector has a sensitive volume of  $0.0019 \text{ mm}^3$  as shown in Table 4.1, active detection area of  $0.8 \times 0.8 \text{ mm}$  with 0.3 mm from top and 4.3 mm from end. Its sensitivity is  $32 \text{ nC/Gy}$ , impedance  $> 200 \text{ mega-ohm}$  at 10 mV reverse bias [15].



Figure 4.4 EDGE™ detector

#### 4.1.5 Stereotactic diode detector (SFD)

Figure 4.5 displays the Stereotactic Field Diode detector (SFD) of ScanditronixWellhofer. The detector has diameter of active area 0.6 mm as shown in Table 4.1, effective measurement point  $0.5 \pm 0.15$  mm, chip size(side/thickness)0.95/0.5 mm. Its geometric form of active area is circular and thickness of active volume is 0.06 mm. It has a sensitive volume of  $0.017 \text{ mm}^3$ [16].



Figure 4.5 Stereotactic Field Diode detector (SFD)

#### 4.1.6 Photon Field Diode detector (PFD)

Photon Field Diode detector (PFD) of ScanditronixWellhofer as shown in Figure 4.6 and Table 4.1 has diameter of active area 2 mm, effective measurement point  $0.5 \pm 0.15$  mm, chip size(side/thickness)2.5/0.5 mm. Its geometric form of active area is circular and thickness of active volume is 0.06 mm. It has a sensitive volume of  $0.2\text{-}0.3 \text{ mm}^3$ [16].



Figure 4.6 Photon Field Diode detector (PFD)

**Table 4.1** Specification for the three diode detectors

Detector	Sensitive volume(mm <sup>3</sup> )	Diameter of active area (mm)	Thickness (mm)	Detector material
EDGE™ detector	0.0019	0.8×0.8	Wall thickness 0.13 mm	n-type silicon diode
Stereotactic Field Diode detector (SFD)	0.017	0.6	Chip size (side/thickness) 0.9/0.5mm	p-type silicon diode
Photon Field Diode detector (PFD)	0.2-0.3	2	Chip size (side/thickness) 2.5/0.5mm	p-type silicon diode

#### 4.1.7 Film dosimeter

The Kodak EDR 2 as displayed in Figure 4.7, Ready-pack film (Carestream Health, Inc. RochesterNY) was employed in this study. The response of the film ranges between 25 and 400 cGy and the saturation exposure is about 700 cGy. The size of the film is 10×12 inches (25.4×30.5 cm<sup>2</sup>). This film was used as a reference detector for this study due to high spatial resolution[17].

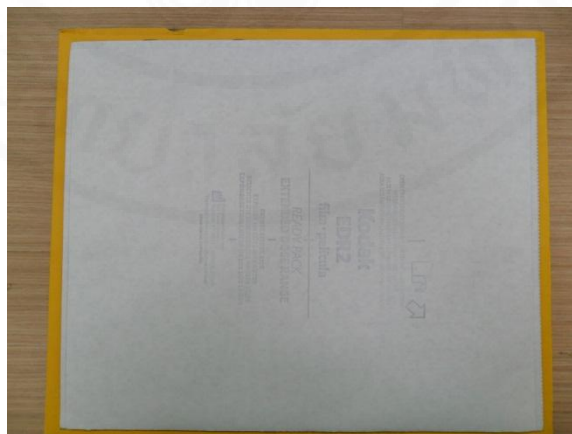


Figure 4.7 Kodak EDR 2

The GafChromic® EBT2 film of International Specialty Product displayed in Figure 4.8 was employed in this study also. The response of the film ranges between 1 cGy and 10 Gy. The size of the film is 8×10inches (20.3×25.4 cm<sup>2</sup>). This film was used as a reference detector for this study due to high spatial resolution and near tissue equivalence[18].

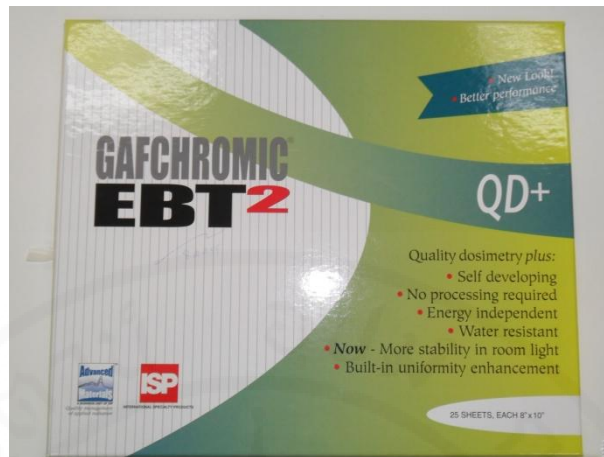


Figure 4.8 GafChromic<sup>®</sup> EBT2 film

#### 4.1.8 Electrometer

The DOSE-1 Electrometer from IBA Dosimetry as shown in Figure 4.9 was used. The power supply is 100-240 V at frequency of 50/60 Hz. It can display the measured value of dose in Gy, Sv, R, rad, or rem. Measuring modes/range is charge (dose): from 40 pC to 1.0 C at 0.1 pC resolution and current (dose rate): from 40 pA to 1000 nA at 0.1 pA resolution. The time base for rate is second, minute, hour. The interval time range is from 1 to 9999 sec [19].



Figure 4.9 Electrometer Wellhofer

#### 4.1.9 Film digitizer with OmniProI'mRT software

The VIDAR's Dosimetry PRO Advantage(RED) (Vidar systems Corporation, Herndon, VA USA) as displayed in Figure 4.10 was used in this study. The available scanning resolutions are 71, 75, 142, 150, 285, 300 dpi. The available bit depths are 8, 12, 16 and 32 bpp. It contains 65,536 shades of gray providing significantly more information in the penumbral regions. The clinical optical density ranges from 0 to 4.0. The OmniProI'mRT software is treatment plan verification and quality assurance of IMRT, IGRT and Rotational treatments. It compares TPS planned data with measured data and can be used to verify quality assurance such as symmetry, flatness, penumbra and light field radiation field congruence and multiple profile analysis[20].



Figure 4.10 VIDAR's DosimetryPRO Advantage(RED)

4.1.10 The automatic film processor KONICA MINOLTA Model SRX-101A (Konica minolta medical & graphic, inc Tokyo, Japan) is shown in Figure 4.11. The specification is described as the followings: Film transport method: Continuous roller transport, Film type and size: Sheet film 10×10-35×43 cm, Circulation system: Continuous pumping of DEV and FIX solution, Power source: AC 115/120V single phase, 12A, 60Hz. Processing solution volumes DEV tank: 3.9 liters FIX tank: 1.8 liters WASH tank: 1.4 liters[21].



Figure 4.11 The automatic film processor  
KONICA MINOLTA Model SRX-101A

## 4.2 Method

### 4.2.1 The penumbra measurement with film dosimetry

4.2.1.1 Calibration curve of the film Calibration curve measurement were performed for three square field sizes ( $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup>) with three depths (1.5, 10 and 20 cm.). The film was prepared by cutting each film in to four pieces of equal size.

For EDR2 film, this process was done in a dark room and every piece of film was sealed by black adjoining tape to shield it from the brightness. The film was placed in solid water phantom perpendicular to the central axis of the beam. The radiation output is equal to 0.8264 cGy/MU for field size  $10 \times 10$  cm<sup>2</sup> at depth of 10 cm for 100 cm. SAD. The films were irradiated for known dose by using SSD technique. Table 4.3 to 4.5 show the MU setting for exposing film in this study. The unexposed film was processed at the same time in order to determine the fog level. In order to minimize as many variations as possible, each experiment and film

calibrations were performed using film from the same batch. All films were processed under the same condition using an automatic film processor (KONICA MINOLTA Model SRX-101A).

For GafChromic<sup>®</sup>EBT2 film, it was cut for the dimension of 3×3 cm<sup>2</sup>. It was scanned after irradiated 24 hr.. The Vidar film digitizer was used to scan the film. The film scanner was operated with scanning resolution of 71 dpi (dot per inch) and Bit depth 16 bpp. The image J software was used for data analysis to generate calibration curve and penumbral width of each field size and depth. It is a freeware program that can download from <http://rsb.info.gov/ij/>. It can be used with a PC with a Java application version 1.4. It can save the file in 8-bit, 16-bit, 32-bit. These file scan be saved with the extension of TIFF, GIF, JPEG, BMP, DICOM, FITS and raw. Moreover the program is open to the simultaneous analysis of multiple images at the same time.

The MU setting for calibration film measurement using SSD technique were calculated by

$$MU = \frac{PD * 100}{D_0 * \left( \frac{SAD}{SSD + 10} \right)^2 * \%DD_d * S_{cp}}$$

*PD* = Prescribed Dose (cGy)

*D*<sub>0</sub> = 0.8264cGy/MU at d10 cm and 100 cm SAD

*SAD* = Source to axis distance 100 cm

*SSD* = Source to surface distance 100 cm

*%DD* = Percent depth dose

*d* = Measured depth

*S*<sub>cp</sub> = Output factor

In the experiment, the output factor and Percent depth dose were measured by Stereotactic diode detector (SFD) and Percent depth dose were normalized at 10 cm depth. In the calculation, parameter values in Table 4.2 were used for monitor unit calculation.

**Table 4.2** The Output factor and Percent depth dose for field size 1×1 ,2×2 and 3×3 cm<sup>2</sup> at depth of 1.5 ,10 and 20 cm.

Field size(cm <sup>2</sup> )	Output factor(S <sub>cp</sub> )	Percent depth dose(%DD)		
		d=1.5 cm	d=10cm	d=20cm
1×1	0.67045	176.7	100	52.32
2×2	0.74965	171.9	100	53.09
3×3	0.79124	166.3	100	52.63

**Table 4.3** The MU settings to irradiate the films in calibration curve measurement for field sizes of 1×1 cm<sup>2</sup> at depths of 1.5,10 and 20 cm.

d =1.5 cm		d=10 cm		d=20 cm	
Dose(cGy)	MU	Dose(cGy)	MU	Dose(cGy)	MU
6.85	7	7.76	14	8.99	31
19.58	20	22.72	41	26.67	92
25.46	26	29.92	54	35.66	123
63.64	65	74.80	135	89.29	308
89.10	91	105.28	190	124.95	431
101.82	104	120.24	217	142.92	493
108.68	111	127.44	230	151.62	523
114.55	117	135.20	244	160.61	554

**Table 4.4** The MU settings to irradiate the films in calibration curve measurement for field sizes of  $2 \times 2 \text{ cm}^2$  at depths of 1.5, 10 and 20 cm.

d = 1.5 cm		d = 10 cm		d = 20 cm	
Dose(cGy)	MU	Dose(cGy)	MU	Dose(cGy)	MU
6.39	6	7.43	12	8.88	27
19.17	18	22.30	36	26.64	81
25.56	24	29.74	48	35.85	109
63.90	60	74.97	121	89.14	271
89.46	84	104.70	169	124.99	380
102.24	96	120.19	194	142.75	434
108.63	102	127.63	206	151.63	461
115.02	108	135.06	218	160.51	488

**Table 4.5** The MU settings to irradiate the films in calibration curve measurement for field sizes of  $3 \times 3 \text{ cm}^2$  at depths of 1.5, 10 and 20 cm.

d = 1.5 cm		d = 10 cm		d = 20 cm	
Dose(cGy)	MU	Dose(cGy)	MU	Dose(cGy)	MU
6.52	6	7.19	11	8.95	26
19.57	18	22.23	34	26.84	78
25.01	23	30.08	46	35.79	104
64.16	59	75.20	115	89.14	259
89.17	82	105.28	161	124.93	363
102.22	94	120.32	184	142.83	415
108.75	100	127.51	195	151.77	441
115.27	106	134.71	206	160.72	467

4.2.1.2 The penumbra measurement with film dosimetry. The beam profile measurement using EDR2 film and GafChromic<sup>®</sup> EBT2 film was operated on the same day as those for the film characterization for field size of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3 \text{ cm}^2$  using SSD of 100 cm set to the top of solid water phantom and film

was placed at depth of  $d_{\max}$ (1.5 cm), 10 and 20 cm perpendicular to the central axis. The dose of 85 cGy was given to film at depth of 1.5 cm, 100 cGy for depth 10cm and 119 cGy for depth 20cm. A thickness of 15 cm solid water phantom was placed under the film for all irradiations to obtain full back scatter radiation. The MU settings for film irradiation were shown in Table 4.6. All films were developed with the automatic film processor. GafChromic<sup>®</sup>EBT2 film was scanned after irradiated 24 hr. The Vidar film digitizer was used to scan the film. The film scanner was operated with scanning resolution of 71 dpi (dot per inch) and Bit depth 16 bpp. The image J software was used for data analysis to generate calibration curve and penumbral width of each field size and depth. The results of measurement were normalized to 100% at the central axis of the beam. Moreover, The penumbral width and standard deviation of penumbral width were found from the average of three repeated measurements using film dosimetry.

**Table 4.6.** The MU settings for irradiating EDR2 film and GafChromic<sup>®</sup>EBT2 film to obtain beam profile measurement

Field size(cm <sup>2</sup> )	MU		
	d=1.5 cm.	d=10 cm.	d=20 cm.
1×1	87	180	411
2×2	80	161	362
3×3	78	153	346

#### 4.2.2 The diode measurement with the Blue phantom (ScanditronixWellhoferDosimetric, Schwarzenbruc, Germany)

##### 4.2.2.1. Setup Blue Phantom<sup>2</sup>

The Blue phantom<sup>2</sup> was setup and adjusted so that the phantom's cross hairs in the X and Y direction are superimposed to the cross-hair of the light field at maximum field size and the intersection point of the cross-hairs is at the isocenter. After that water was filled to the phantom and SSD of 100 cm was set at the water surface. A spirit level was used for checking water level in x, y, and z directions. The leveling frame mounted on the top of the lift table was used to adjust in

vertical and horizontal directions of the tank. Common Control Unit (CCU) was used to give the voltage supply to drive the detectors in the tank and also provide the connection between detectors and a PC with Omnipro-Accept V7.2 via the Ethernet cable.

#### 4.2.2.2. Setup detectors

The CC13 ionization chamber and its alignment cap were used for checking the water level of the Blue Phantom<sup>2</sup>. The chamber with white alignment cap as shown in Figure 4.12 was placed in a holder of the phantom and was moved to a corner of the phantom by using hand control which far about 5 cm from each wall and at water surface. The alignment cap was rotated to 45 degree toward the water surface as shown in Figure 4.13. The lines at the cap was adjusted until obtaining a cross line. After that the chamber was moved to the next corner of the phantom. Then if the lines of the cap does not form a cross line, it means that the water tank is not level. The leveling screw at that corner was loosed and rotated until the lines forming the cross again. The remaining two corners are in the same process. Then CC 13 detector with white alignment cap was removed. Diode was placed in a special holder. The axis of PFD and SFD was set parallel to the central axis but the axis of EDGE detector was set perpendicular to the central axis. The detector was moved along x, y, and z direction in order to check whether the center of the detector aligns to the crosshair or not. After that the surface of the detector was positioned at the central axis and the water surface by using the hand control. The effective point of measurement of PFD, SFD and EDGE are less than 0.9 mm therefore the surface of the detectors was set exactly at the water surface. The setup of PFD, SFD and EDGE detectors are shown in Figure 4.14, 4.15, and 4.16 respectively.

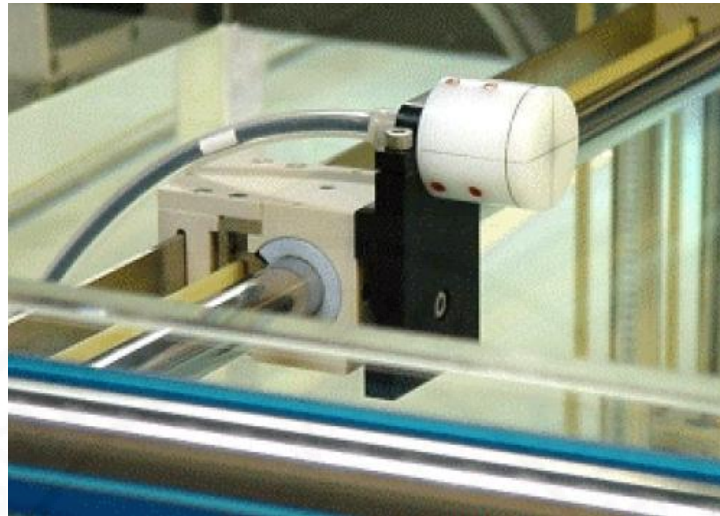


Figure 4.12 Alignment cap mounted on the CC13

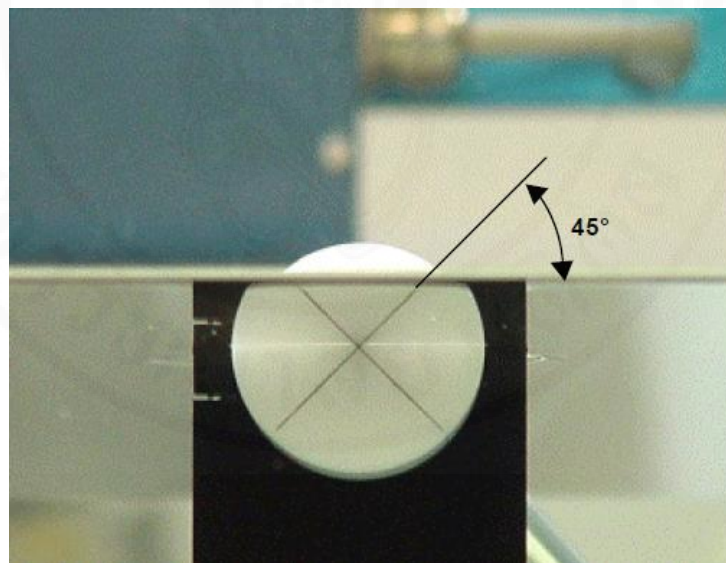


Figure 4.13 Alignment cap from below the water surface line

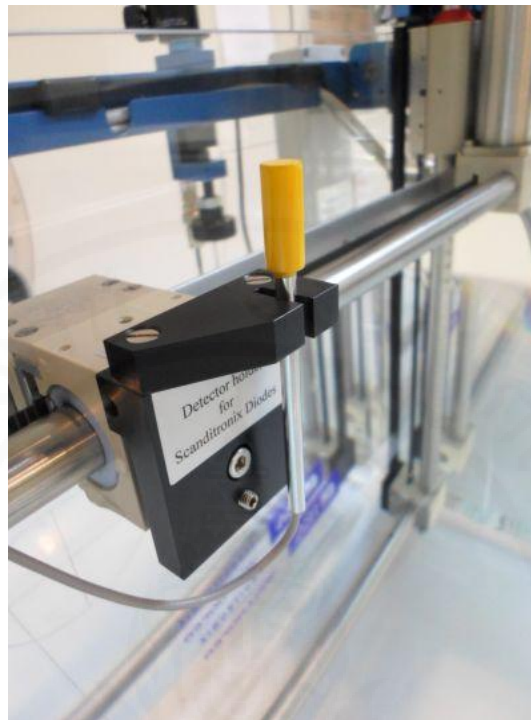


Figure 4.14 The setup of Photon Field Diode detector (PFD)

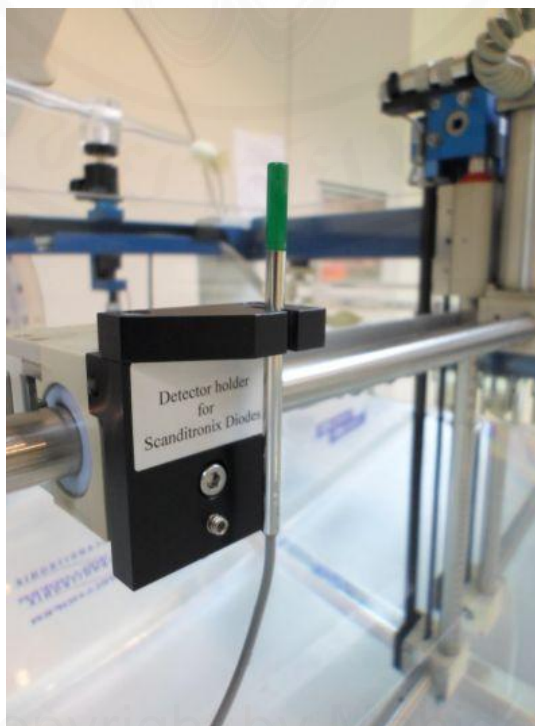


Figure 4.15 The setup of Stereotactic Field Diode detector (SFD)

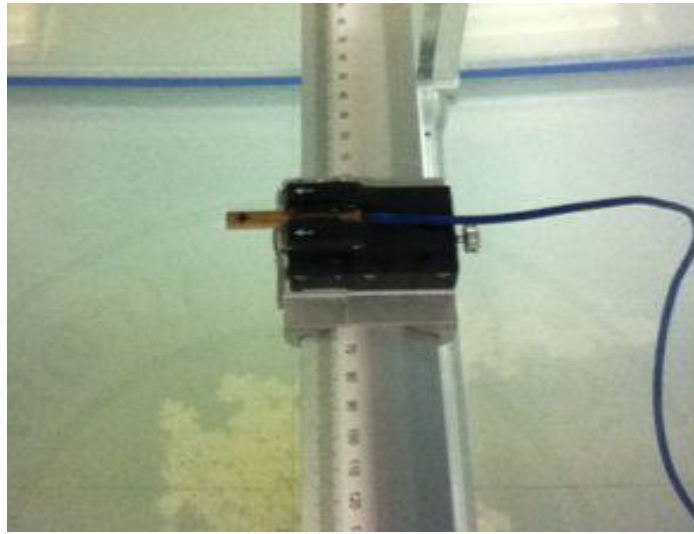


Figure 4.16 The setup of EDGE™ detector

#### 4.2.2.3. Setup program

Firstly, a queue was created to define radiation device, field size, depth, energy, detector, phantom, and SSD. The crossline direction was selected to measure beam profile which is along the X axis. The position of the detector was set by defining isocenter, water surface and normalization position after that background measurement was performed. The beam profile at the depth of maximum dose ( $d_{max}$ ), 10 and 20 cm were used to measure at 6MV photon beams for field size of  $1 \times 1$ ,  $2 \times 2$ , and  $3 \times 3$  cm<sup>2</sup>. The Blue phantom<sup>2</sup> with EDGE detector, Stereotactic diode detector (SFD) and Photon diode detector (PFD) were used to measure beam profiles for field size of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup> at the depth of maximum dose ( $d_{max}$ ), 10 and 20 cm. In this study, step by step was used for a scan mode. The step type was chosen as an Equidistant. The scanning step distance was 0.5 mm and scan speed was 1.0 mm/s. The phantom has a position accuracy of  $\pm 0.1$  mm per axis and reproducibility of  $\pm 0.1$  mm. It is run by an external control from the OmniPro-Accept 7.2 Software. All beam profile measurement values were normalized to  $d_{max}$  and generate penumbral width for all field sizes.

## CHAPTER V

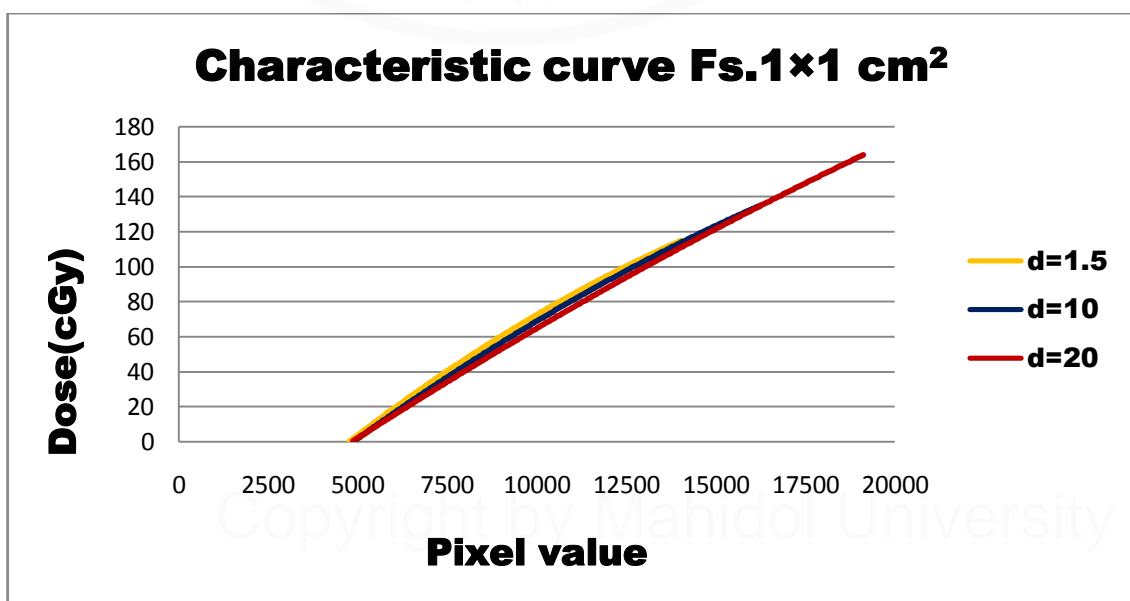
### RESULTS AND DISCUSSION

#### 5.1 Reference film dosimetry

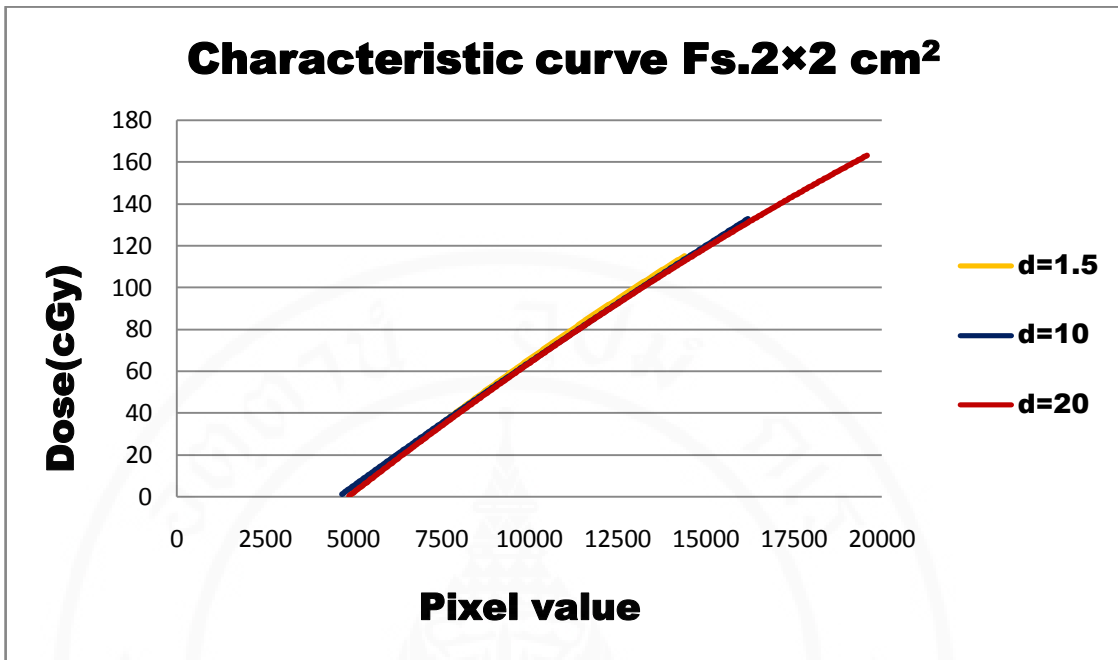
##### 5.1.1 EDR2 radiographic film

###### 5.1.1.1 The calibration curve of EDR2 radiographic film

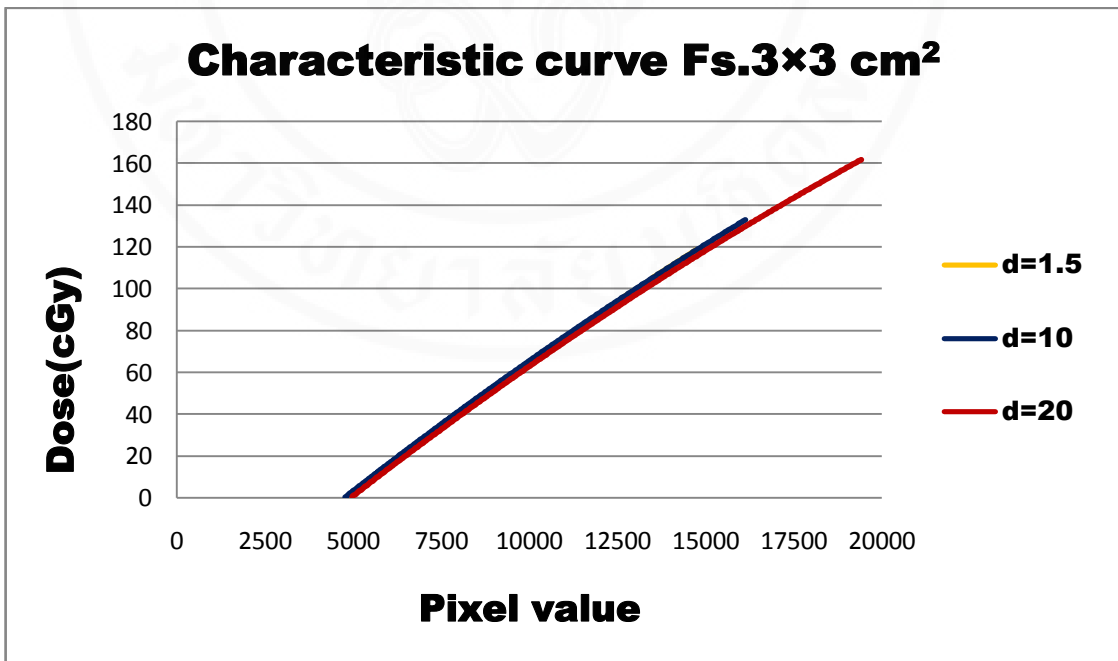
Figure 5.1 (a), (b) and (c) show the calibration curves using EDR2 radiographic film at depths of 1.5, 10 and 20 cm for field sizes of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup>, respectively. Figure 5.2 (d), (e) and (f) also show the EDR2 calibration curves but they were to compare the field size-dependence at each depth. These films were irradiated for known dose using SSD technique and the image J software was used for data analysis and generating calibration curves. The best-fitting of the curves in Microsoft Excel were performed using a polynomial equation of degree 2. The agreement of the fittings is reported in Table 5.1 The R-squared value is approximately greater than 0.999 which showed that the polynomial equation of degree 2 is suitable to predict the calculated data closed to the measured one.



(a) Field size  $1 \times 1$  cm<sup>2</sup>

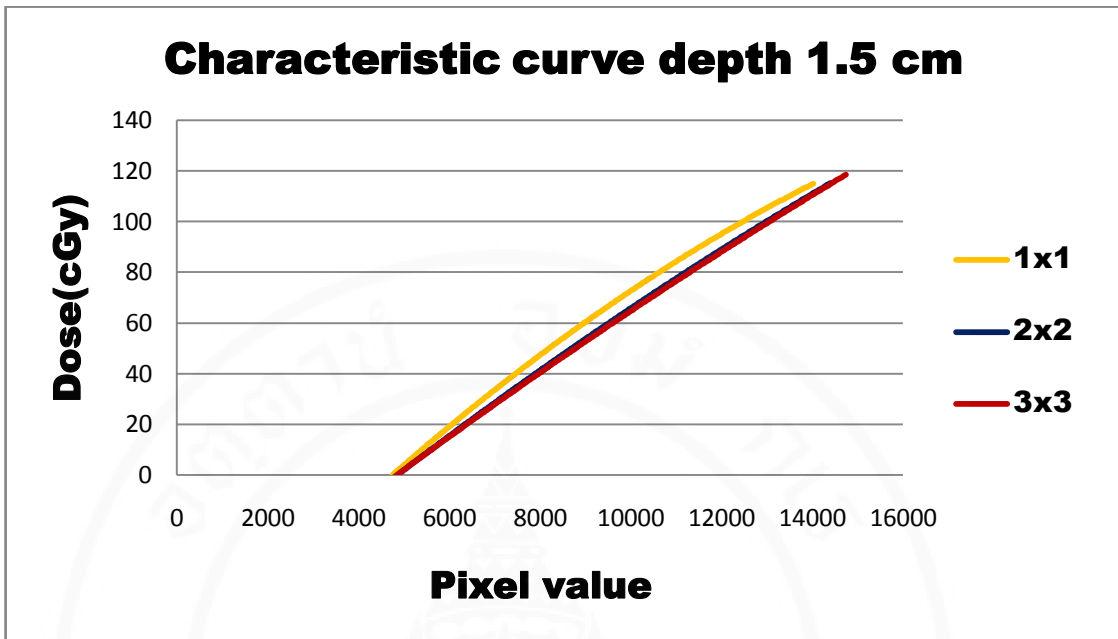


(b) Field size 2×2 cm<sup>2</sup>

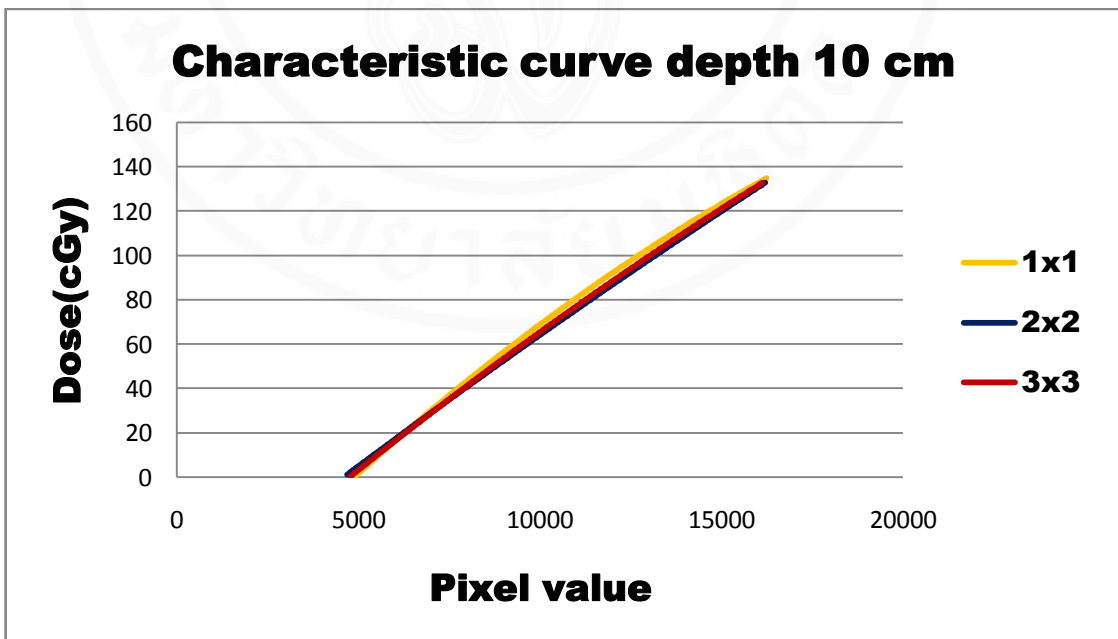


(c) Field size 3×3 cm<sup>2</sup>

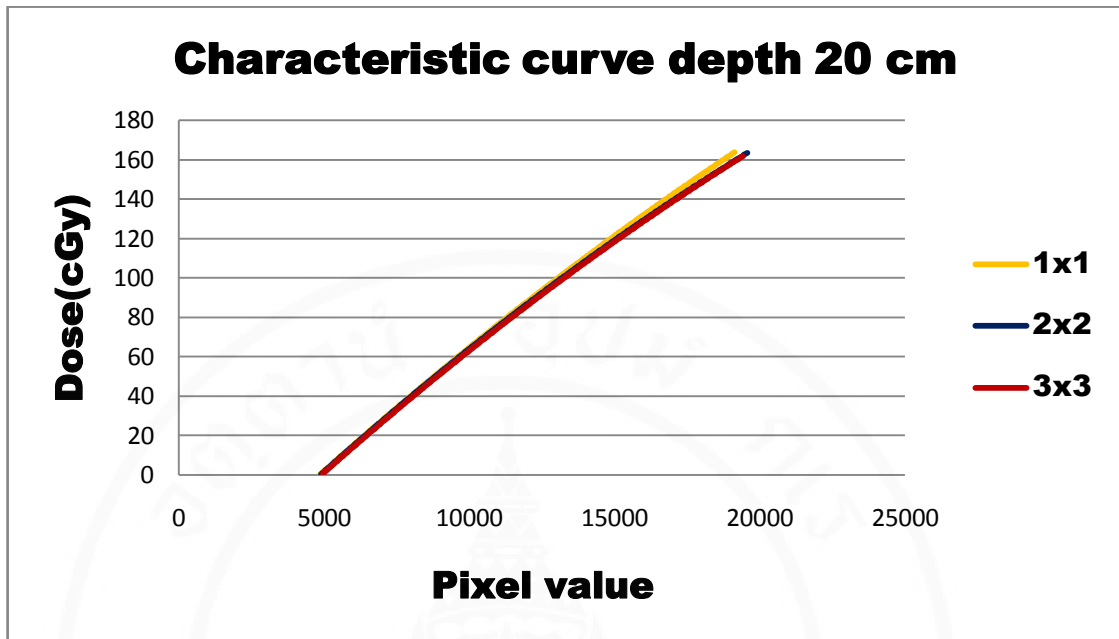
**Figure 5.1 (a-c)** The calibration curve using EDR2 radiographic film of field size 1×1 , 2×2 and 3×3 cm<sup>2</sup> at depth 1.5,10 and 20 cm.



(d) depth 1.5 cm.



(e) depth 10 cm



(f) depth 20 cm

**Figure 5.2 (d-f)** The calibration curve using EDR2 radiographic film at depth 1.5, 10 and 20 cm of field size 1×1 , 2×2 and 3×3 cm<sup>2</sup>

**Table 5.1** The R-squared value( $R^2$ ) of EDR2 film's calibration curves using a polynomial equation of degree 2 to fit the curves.

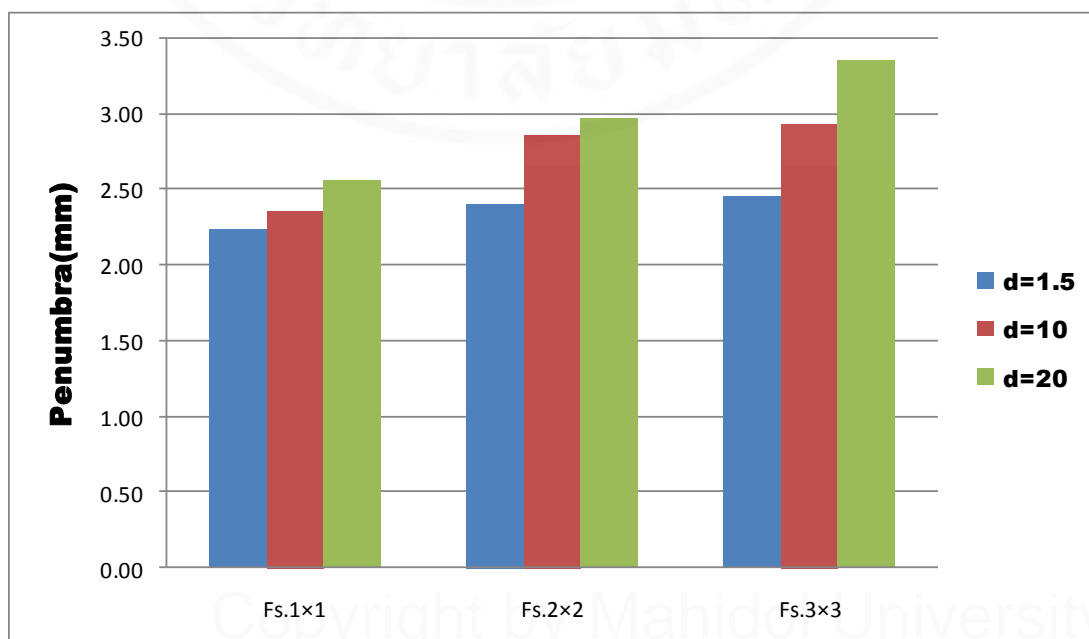
Field size(cm <sup>2</sup> )	Depth (cm)	R-squared value( $R^2$ )
1×1	1.5	0.99945
	10	0.99914
	20	0.99845
2×2	1.5	0.99872
	10	0.99913
	20	0.99896
3×3	1.5	0.99731
	10	0.99938
	20	0.99905

Robar and Clark [22] found that the effect of phantom scatter dose is somewhat negligible while increasing depths for field sizes less than 4 cm. It causes fewer amounts of low energies when increasing depths. For that reason the EDR2 film even though contained high Z materials obtained almost the same response of calibration curves when increasing depths for field sizes of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup>.

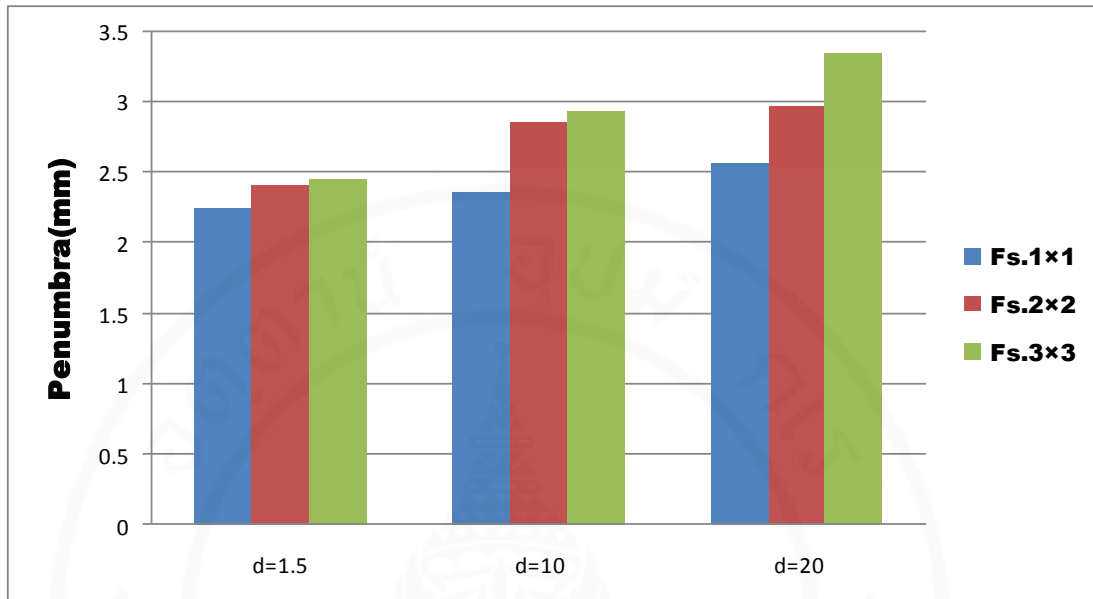
Nevertheless the calibration curve for each depth and field size was still employed for determining dose calculation in order to minimize other variations as many as possible such as film processing conditions.

5.1.1.2 The penumbral width measured by the EDR2 radiographic film

Figure 5.3 (a) shows the penumbral width using EDR2 radiographic film for field size of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup> at different depths. Figure 5.4 (b) displays the penumbral width using EDR2 radiographic film at depths of 1.5, 10 and 20 cm with various field sizes. In this experiment, three repeated measurements were performed and the image J software was used for data analysis and generated penumbral width (20-80%). Table 5.2 shows the penumbral widths and the standard deviation obtained using the polynomial equation of degree 2.



**Figure 5.3 (a)** The comparison of penumbral width using EDR2 radiographic film for field size of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$  cm<sup>2</sup> at different depths.



**Figure 5.4 (b)** The comparison of penumbral width using EDR2 radiographic film of depth at 1.5, 10 and 20 cm with various field sizes.

**Table 5.2** The penumbral width and standard deviation of penumbral width from the average of three repeated measurements using EDR2 radiographic film

Field size(cm <sup>2</sup> )	Depth (cm)	Average penumbral width(mm)	SD
1×1	1.5	2.24	0.05
	10	2.36	0.06
	20	2.57	0.08
2×2	1.5	2.41	0.06
	10	2.86	0.16
	20	2.97	0.11
3×3	1.5	2.45	0.06
	10	2.94	0.21
	20	3.35	0.36

The lowest penumbral width is 2.24 mm obtained at depth of 1.5 cm and field size of  $1 \times 1 \text{ cm}^2$  and the highest one is 3.35 mm showed at depth of 20 cm and field size of  $3 \times 3 \text{ cm}^2$  and the maximum SD appears at depth of 20 cm and field size of  $3 \times 3 \text{ cm}^2$  as shown in Table 5.2. In Figure 5.2 (a), at field size of  $1 \times 1 \text{ cm}^2$ , when depth increases, the penumbral width goes up slightly. In contrast, at field size of  $3 \times 3 \text{ cm}^2$ , penumbral width rises sharply when depth increases. At the same notice, in Figure 5.2 (b), the penumbral width has small changes when field size increases at depth of 1.5 cm but it alters substantially when field size increases at depth of 20 cm.

There are two possible reasons. The first one might be caused by the large amount of low energy photons from phantom especially at the biggest field size of  $3 \times 3 \text{ cm}^2$  and the largest depth of 20 cm. But the study of Robar and Clark as mentioned before showed that for field sizes less than 4 cm, the amount of low energy photons from phantom were less when depth increased. It might be the second reason which is EDR2 film still has the effect of energy dependence due to its high atomic number materials composition[22].

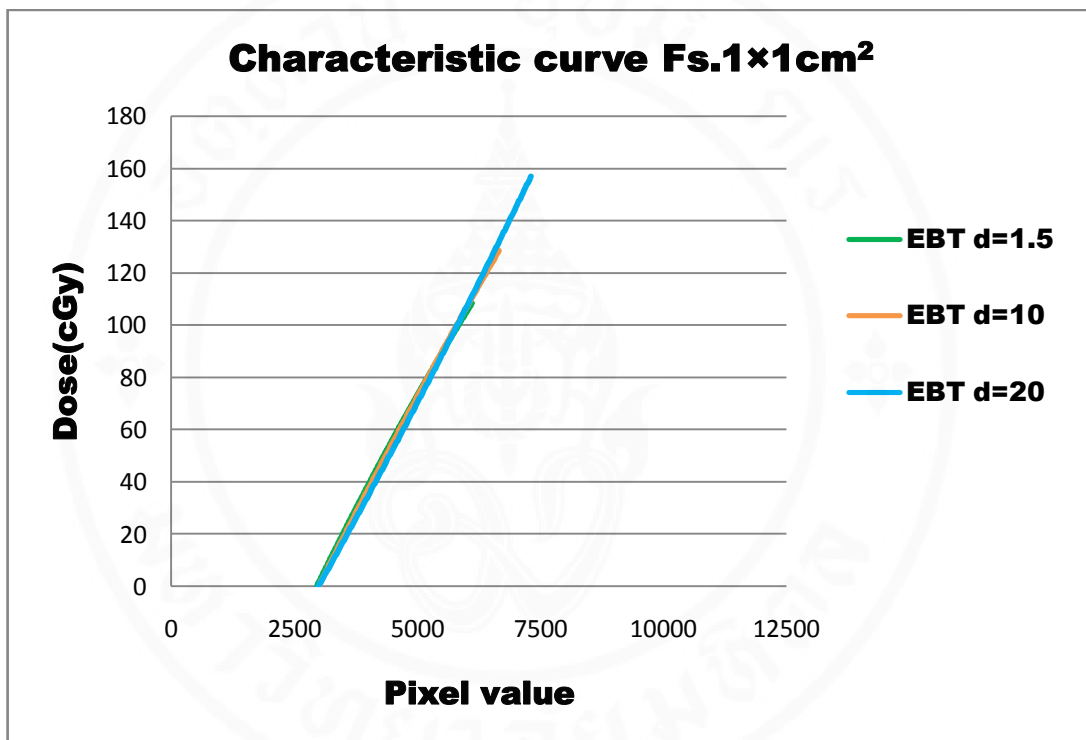
Sang GyuJu et al showed that EDR2 film had energy dependence. Using lead filters (to get rid of the scatter low energy) could be achieved higher accuracy for IMRT verification than EDR2 without filters compared with GafChromic<sup>®</sup>EBT2 film's result. Therefore in our study GafChromic<sup>®</sup>EBT2 film was used as a second reference because it contains more tissue equivalent composition caused less energy dependence[23].

### 5.1.2 GafChromic<sup>®</sup>EBT2 film

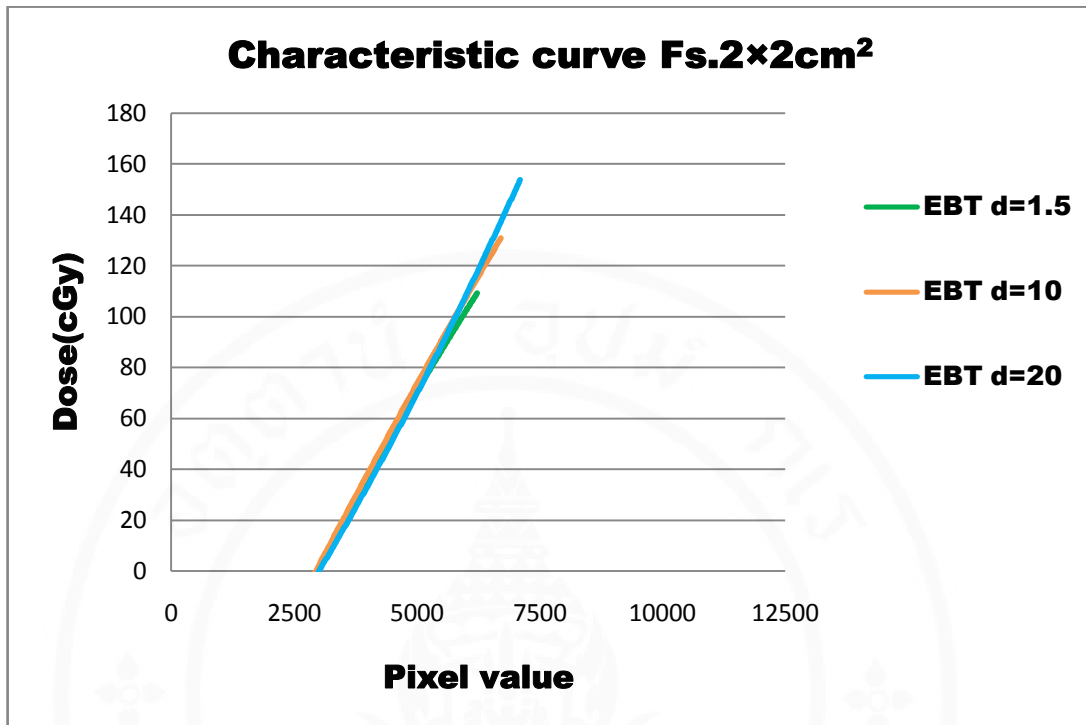
#### 5.1.2.1 The calibration curve of GafChromic<sup>®</sup>EBT2 film

Figure 5.5 (a), (b) and (c) show the calibration curves using GafChromic<sup>®</sup>EBT2 film at depths of 1.5, 10 and 20 cm for field sizes of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3 \text{ cm}^2$ , respectively. Figure 5.6 (d), (e) and (f) also show the GafChromic<sup>®</sup>EBT2 film calibration curves but they were to compare the field size-dependence at each depth. Like the EDR2 film measurement's procedure, GafChromic<sup>®</sup>EBT2 film was irradiated for known dose using SSD technique and the image J software was used for data analysis and generating calibration curves. The curves were fitted using both a linear

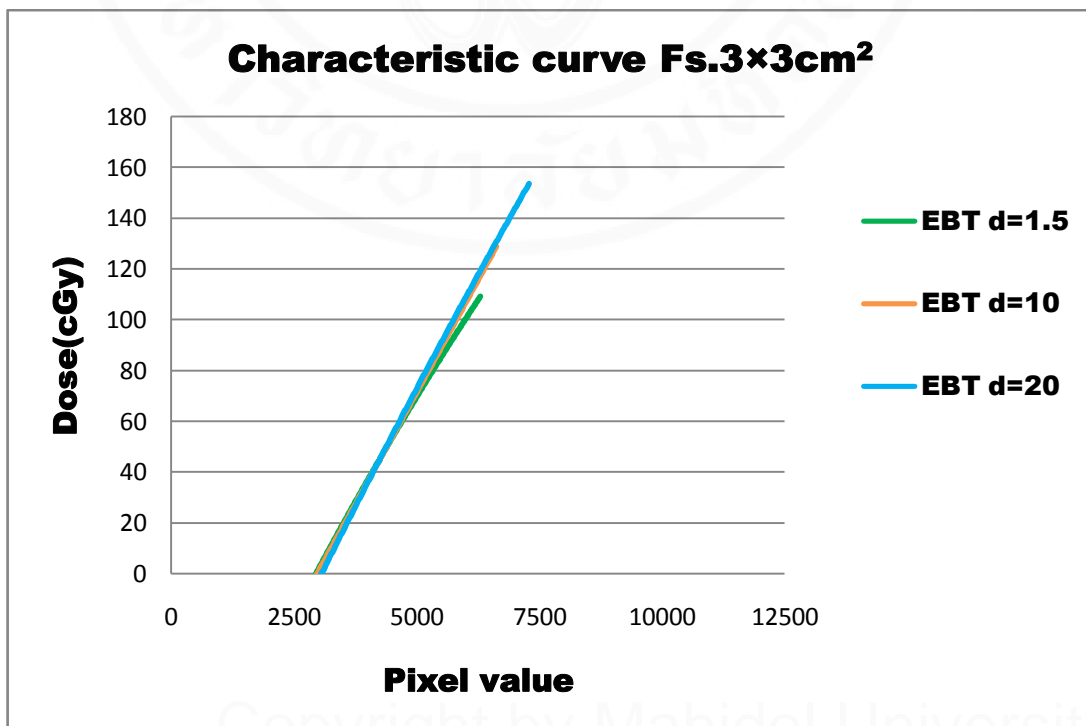
equation and polynomial equation of degree 2. It was found that there is no significant difference between both equations as determined by independent samples T-test ( $p = 0.743$ ). However the polynomial equation of degree 2 appears slightly better for fitting the curves as shown in Table 5.3 so it was selected for the penumbral width calculation.



(a) Field size 1×1 cm<sup>2</sup>

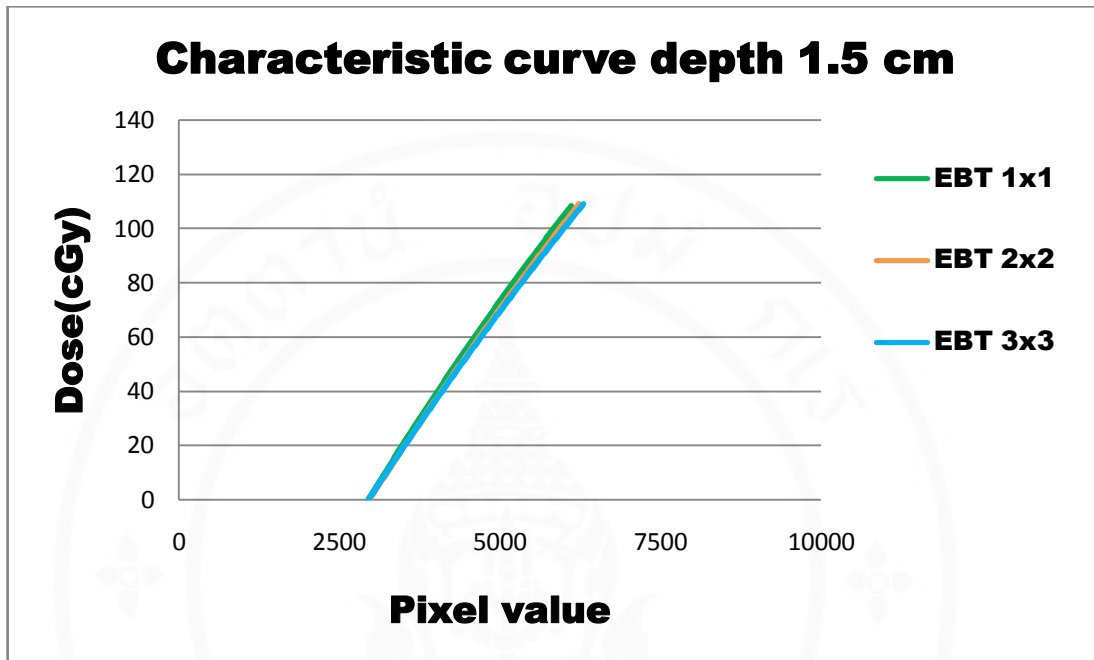


(b) Field size 2×2 cm<sup>2</sup>

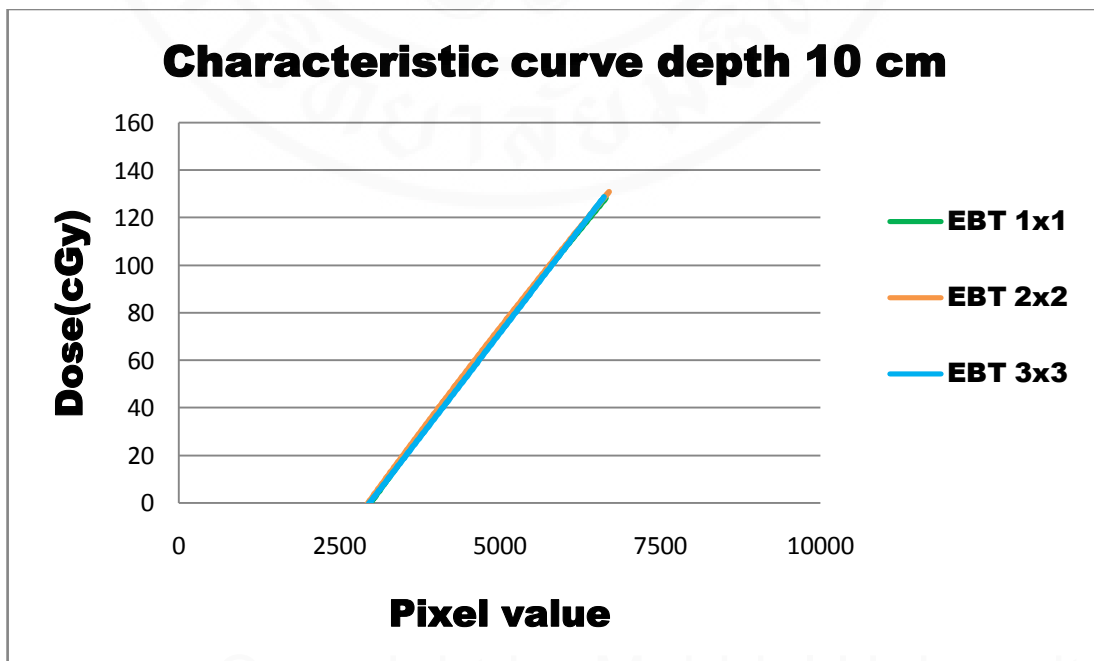


(c) Field size 3×3 cm<sup>2</sup>

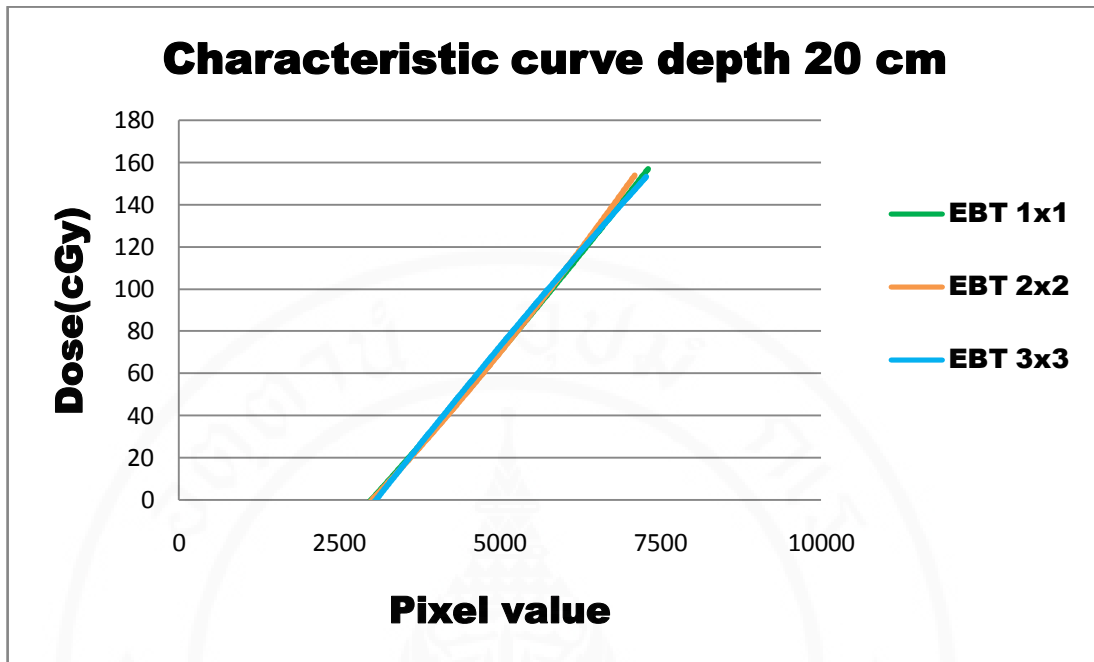
**Figure 5.5 (a-c)** The calibration curve using GafChromic<sup>®</sup>EBT2 film of field size 1×1, 2×2 and 3×3 cm<sup>2</sup> at depth 1.5,10 and 20 cm.



(d) depth 1.5 cm.



(e) depth 10 cm



(f) depth 20 cm

**Figure 5.6 (d-f)** The calibration curve using GafChromic®EBT2 film at depth 1.5,10 and 20 cm of field size 1×1 , 2×2 and 3×3 cm<sup>2</sup>

**Table 5.3**The R-squared value(R<sup>2</sup>) of GafChromic®EBT2 film’s calibration curves using a linear equation and polynomial equation of degree 2 to fit the curves.

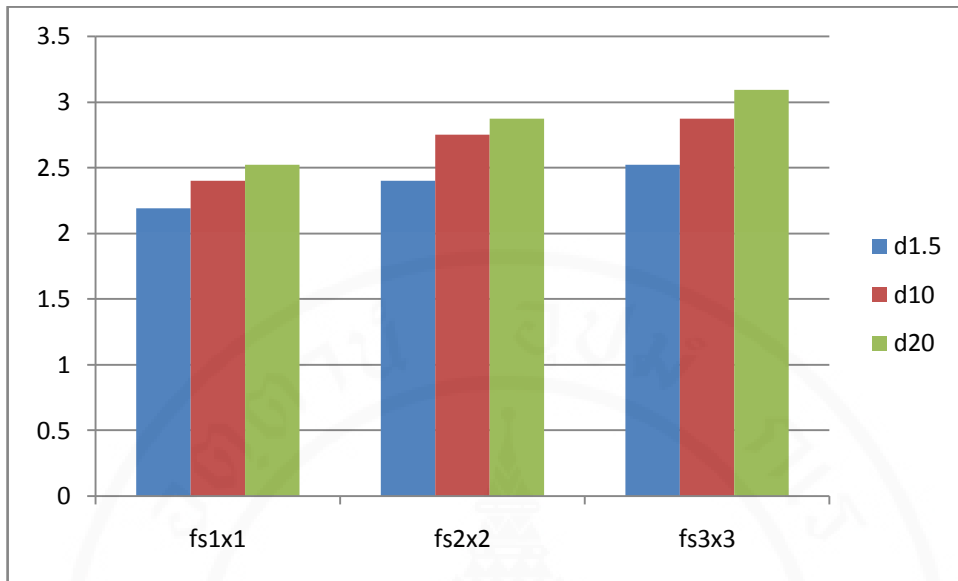
Field size(cm <sup>2</sup> )	Depth (cm)	Linear equation	polynomial equation of degree 2
1×1	1.5	0.990108	0.99073
	10	0.99276	0.99298
	20	0.99714	0.99736
2×2	1.5	0.99111	0.99150
	10	0.99386	0.99402
	20	0.99456	0.99536
3×3	1.5	0.99185	0.99231
	10	0.99198	0.99198
	20	0.99494	0.99514

#### 5.1.2.2. Measurement of penumbral width using GafChromic<sup>®</sup>EBT2 film

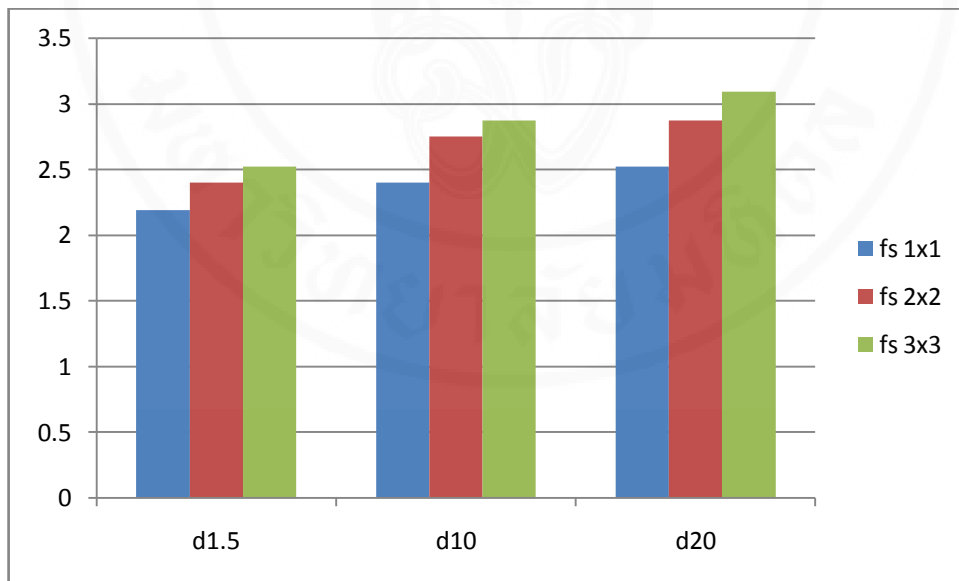
The lowest penumbral width is 2.19 mm obtained at depth of 1.5 cm and field size of  $1 \times 1 \text{ cm}^2$  and the highest one is 3.09 mm showed at depth of 20 cm and field size of  $3 \times 3 \text{ cm}^2$  and the maximum SD appears at depth of 20 cm and field size of  $3 \times 3 \text{ cm}^2$  as presented in Table 5.4 The penumbral width increase when depths and field sizes increase. In Figure 5.7 (a), at field size of  $1 \times 1 \text{ cm}^2$ , when depth increases, the penumbral width goes up slightly. In contrast, at field size of  $3 \times 3 \text{ cm}^2$ , penumbral width rises sharply when depth increases. At the same observation, in Figure 5.8 (b), the penumbral width has small changes when field size increases at depth of 1.5 cm but it alters substantially when field size increases at depth of 20 cm. Moreover the increasing gradient of penumbral width is the same for both in Figure 5.3 (a) and 5.4(b).

**Table 5.4** The penumbral width and standard deviation of penumbral width from the average of three repeated measurements using GafChromic<sup>®</sup>EBT2 film.

Field size( $\text{cm}^2$ )	Depth (cm)	Penumbral width(mm) average	SD
1×1	1.5	2.19	0.07
	10	2.40	0.05
	20	2.52	0.11
2×2	1.5	2.40	0.05
	10	2.75	0.16
	20	2.87	0.19
3×3	1.5	2.52	0.11
	10	2.87	0.11
	20	3.09	0.30



**Figure 5.7 (a)** The comparison of penumbra width using GafchromicEBT2 film for field size of 1×1, 2×2 and 3×3 cm<sup>2</sup> at different depths.

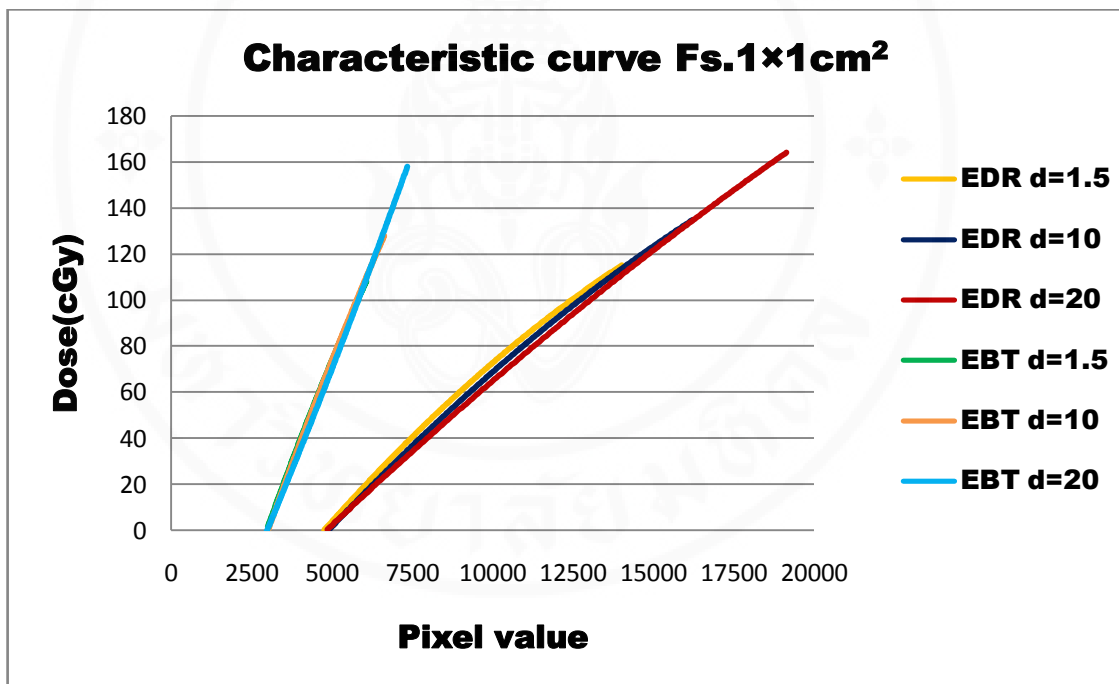


**Figure 5.8 (b)** The comparison of penumbral width using GafchromicEBT2 film of depth at 1.5, 10 and 20 cm with various field sizes.

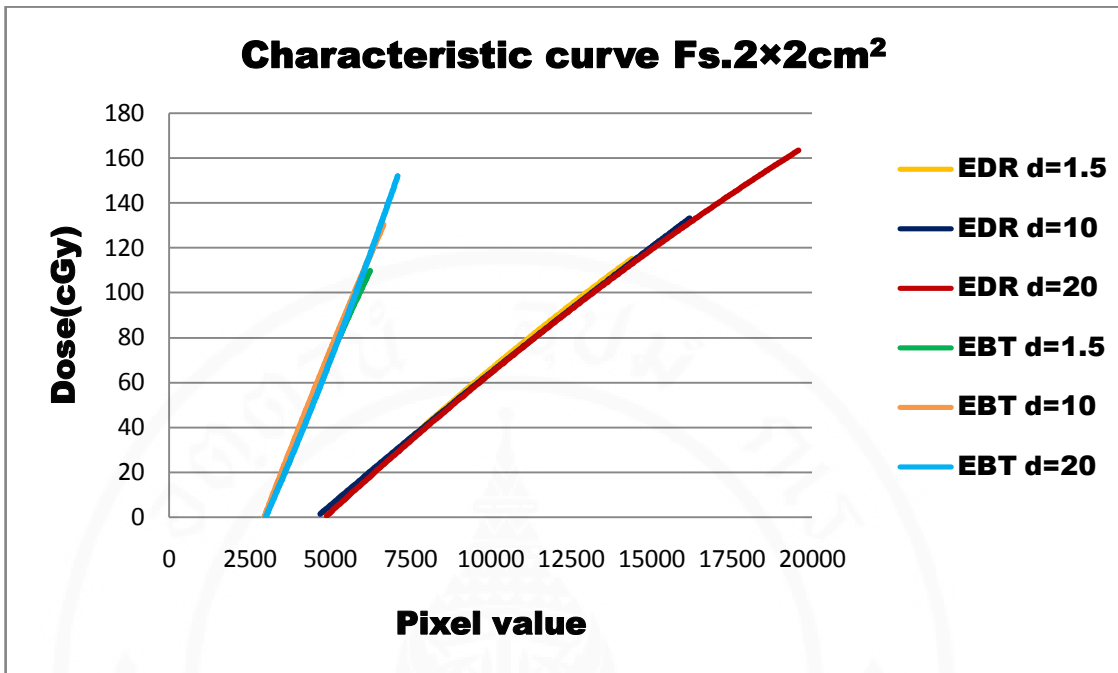
### 5.1.3 Penumbral width comparison between Kodak EDR2 radiographic and GafChromic® EBT2 film

#### 5.1.3.1 Calibration curves comparison

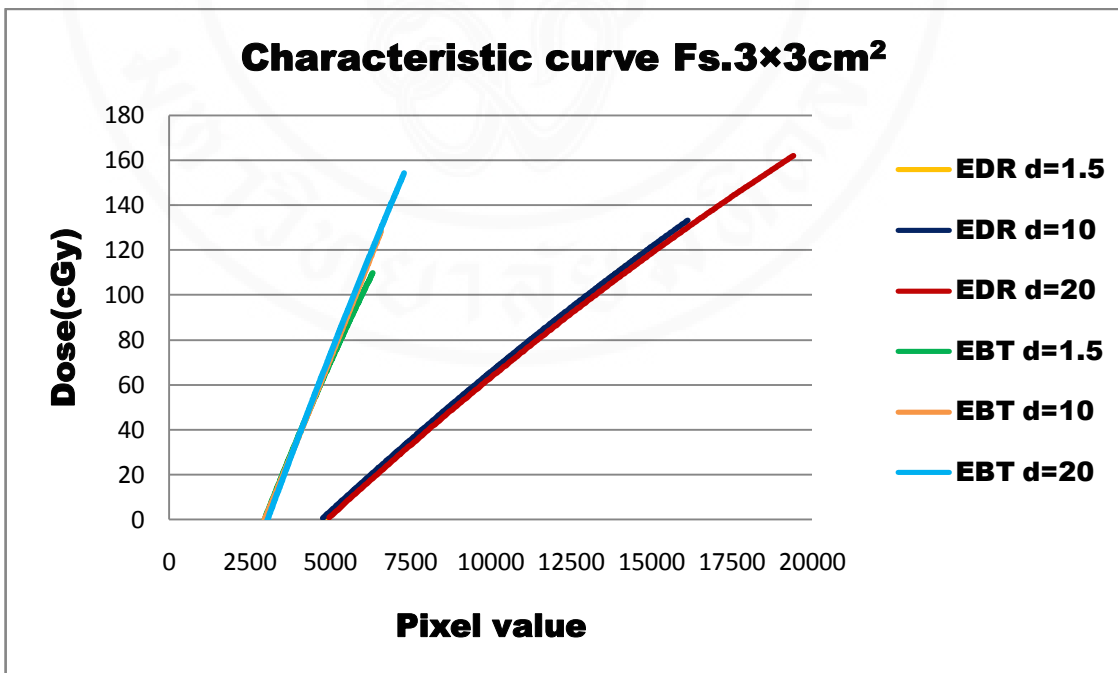
Figure 5.9 (a-c) present the comparison of calibration curves between EDR2 radiographic film and EBT2 film for field size of  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$   $\text{cm}^2$  with different depths. The EDR2 goes up less sharply than the EBT2 film when dose increases which means that it shows substantial less sensitivity to dose than EBT2 film. However their calibration curves show no field size and depth dependence, it might be because of our ranges of field sizes and depths still have less amount of low energies as mentioned by Robar and Clark [21].



(a) Field size  $1 \times 1 \text{ cm}^2$



(b) Field size 2×2 cm<sup>2</sup>



(c) Field size 3×3cm<sup>2</sup>

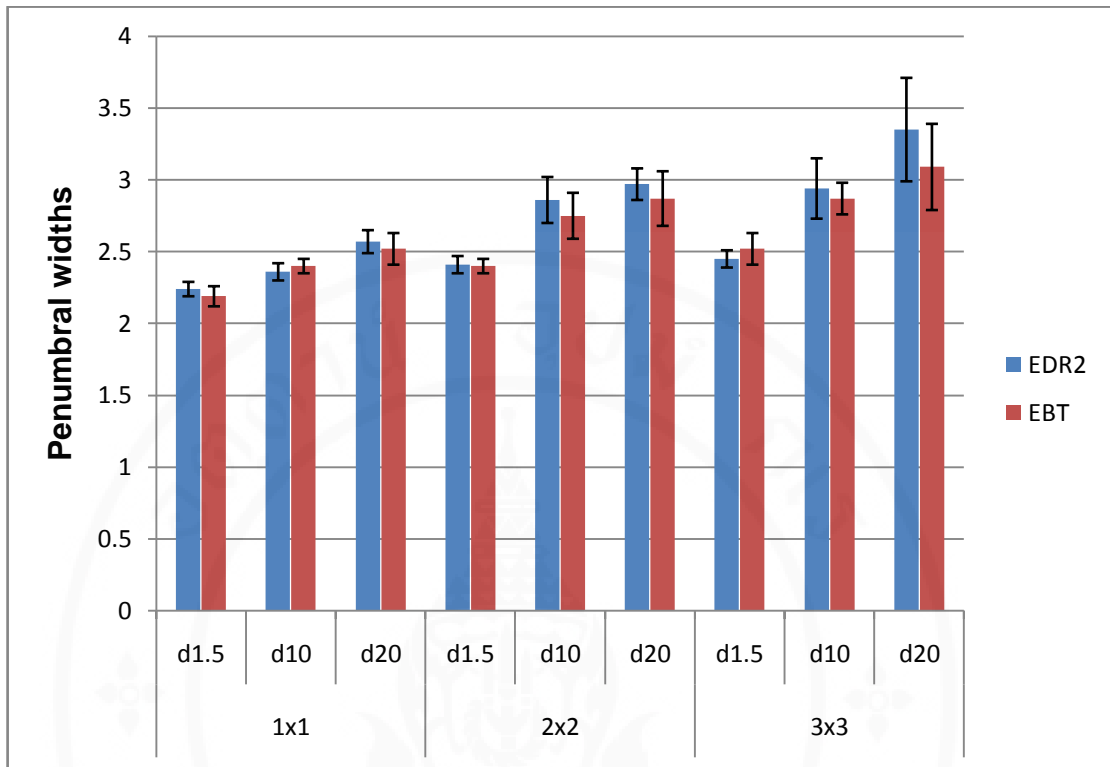
**Figure 5.9 (a-c)** The comparison of calibration curve between Kodak EDR2 radiographic film and Gafchromic EBT2 radiochromic film for field size of 1×1, 2×2 and 3×3 cm<sup>2</sup> at depth of 1.5, 10 and 20 cm.

### 5.1.3.2 The penumbral widths comparison

Figure 5.10 shows the penumbral widths obtained from EDR2 and EBT2 film at depth of 1.5, 10, and 20 cm for field size of  $1\times 1$ ,  $2\times 2$ , and  $3\times 3$  cm<sup>2</sup>. It can be observed that penumbral widths measured with EDR2 were larger than those measured with EBT2 film for almost all depths and field sizes. The maximum difference of penumbral width can be observed at depth of 20 cm for field size of  $3\times 3$  cm<sup>2</sup> which is 0.26 mm as shown in Table 5.5 Also the maximum standard deviation appears at depth of 20 cm for field size of  $3\times 3$  cm<sup>2</sup> for both types of film.

As expected, this result can be caused by more energy dependence from EDR2 than EBT2 film. EDR2 comprises silver halide components which are more likely to initiate photoelectric effect causing dose overestimation especially at penumbral region (Cheung *et al* 2006). In contrast, EBT2 consists of low atomic number closer to tissue-equivalent density caused to less photoelectric effect as a result lower energy dependence occurs. That is why penumbral widths measured by EDR2 are larger than that measured by EBT2 film especially at the deepest depth[5].

However it was found that their penumbral widths are not significant difference with  $p$ -value  $> 0.05$  using the independent sample test for all field sizes and depths as shown in Table 5.5 It could be explained by the study of Sutherlands and Rogers[29]. They found that EBT/EBT2 film still has some energy dependence especially below 100 keV energy. They suggested that their effective atomic number still needs more improvement to make them closer to that of water.



**Figure 5.10** The penumbral widths measured with EDR2 and EBT2 film at depths of 1.5, 10, and 20 cm for field size of 1×1, 2×2, and 3×3 cm<sup>2</sup>

**Table 5.5** The difference of penumbra width (80-20%) and *p*-values used for statistical analysis from using Kodak EDR2 radiographic film and GafchromicEBT2radiochromic film

.Field size (cm <sup>2</sup> )	Depth (cm)	Penumbra width(mm) (80-20%)		Difference (EDR2- EBT2)(mm)	<i>p</i> -values
		EDR2±SD	EBT2±SD		
1×1	1.5	2.24±0.05	2.19±0.07	0.05	0.198
	10	2.36±0.06	2.40±0.05	-0.04	0.233
	20	2.57±0.08	2.52±0.11	0.05	0.407
2×2	1.5	2.41±0.06	2.40±0.05	0.05	0.749
	10	2.86±0.16	2.75±0.16	0.11	0.275
	20	2.97±0.11	2.87±0.19	0.09	0.312
3×3	1.5	2.45±0.06	2.52±0.11	-0.07	0.234
	10	2.94±0.21	2.87±0.11	0.07	0.479
	20	3.35±0.36	3.09±0.30	0.26	0.202

*Note:* if *p*-value is less than 0.05, it means “reject null hypothesis” = “significantly different” and vice versa.

## 5.2. Penumbral width comparison between reference film measurements and various diode detectors

### 5.2.1 Penumbral width comparison between EDR2 radiographic film and various diode detectors

Table 5.6 presents the penumbral width (80-20%) using EDR2 radiographic film as a measured reference value to compare with penumbral width measured by Photon diode detector (PFD), Edge detector and Stereotactic field diode

detector (SFD) for field size of 1×1, 2×2, and 3×3 cm<sup>2</sup> at depths of 1.5, 10 and 20 cm in water phantom with SSD = 100 cm.

**Photon field diode detector (PFD)**

Penumbral widths measured by PFD were broader compared with those of EDR2. The maximum difference were presented at field size of 1×1 cm<sup>2</sup> at depths of 10 cm and the average different penumbral width is 0.09 mm.

**EDGE detector**

Penumbral widths obtained from EDGE detector were narrower than those of EDR2. The maximum difference were shown at field size of 2×2 cm<sup>2</sup> at depths of 1.5 and 10 cm. The average different penumbral width is 0.16 mm.

**Stereotactic field diode detector (SFD)**

Penumbral widths acquired from SFD were a lot sharper than those of EDR2. The maximum difference were shown at field size of 2×2 cm<sup>2</sup> at depths of 1.5 and 10 cm. The average different penumbral width is 0.31 mm.

**Table 5.6** Penumbral width (80-20%) (mm) measured with EDR2 radiographic film, Photon field diode detector (PFD), EDGE detector and Stereotactic field diode detector (SFD) for field size of 1×1, 2×2, and 3×3 cm<sup>2</sup> at depths of 1.5, 10 and 20 cm.

Field size (cm <sup>2</sup> )	Depth (cm)	EDR2±SD	PFD		EDGE		SFD	
			Penumbral width(mm) (80-20%)	Diff (EDR2-PFD) (mm)	Penumbral width (mm) (80-20%)	Diff (EDR2-EDGE) (mm)	Penumbral width(mm) (80-20%)	Diff (EDR2-SFD) (mm)
1x1	1.5	2.24±0.05	2.3	-0.06	2	0.24	1.9	0.34
	10	2.36±0.06	2.55	-0.19	2.35	0.01	2.1	0.26
	20	2.57±0.08	2.75	-0.18	2.6	-0.03	2.35	0.22
2x2	1.5	2.41±0.06	2.45	-0.04	2.15	0.26	1.95	0.46
	10	2.86±0.16	2.8	0.06	2.6	0.26	2.4	0.46
	20	2.97±0.11	3.15	-0.18	2.9	0.07	2.85	0.12
3x3	1.5	2.45±0.06	2.52	-0.07	2.2	0.25	2.05	0.4
	10	2.94±0.21	2.95	-0.01	2.75	0.19	2.7	0.24
	20	3.35±0.36	3.33	0.02	3.2	0.15	3.05	0.3

### **5.2.2 Penumbra width comparison between GafChromic<sup>®</sup> EBT2 radiochromic film and various diode detectors**

Table 5.7 presents the penumbra width (80-20%) using EBT2 radiochromic film as a measured reference value to compare with penumbra width measured by Photon diode detector (PFD), EDGE detector and Stereotactic field diode detector (SFD) for field size of 1×1, 2×2, and 3×3 cm<sup>2</sup> at depths of 1.5, 10 and 20 cm in water phantom with SSD = 100 cm.

#### **Photon field diode detector (PFD)**

Penumbra widths measured by PFD were wider compared with those of EBT2. The maximum difference were presented at field size of 2×2 cm<sup>2</sup> at depth of 20 cm. The average different penumbra width is 0.13 mm.

#### **EDGE detector**

Penumbra widths obtained from EDGE detector were thinner than those of EBT2. The maximum difference were shown at field size of 3×3 cm<sup>2</sup> at depth of 1.5 cm. The average different penumbra width is 0.14 mm.

#### **Stereotactic field diode detector (SFD)**

Penumbra widths achieved by SFD were a lot smaller than those of EBT2. The maximum difference were shown at field size of 3×3 cm<sup>2</sup> at depth of 1.5 cm. The average different penumbra width is 0.25 mm.

**Table 5.7** Penumbral width (80-20%) (mm) measured with GafChromic<sup>®</sup> EBT2 radiochromic film, Photon field diode detector (PFD), EDGE detector and Stereotactic field diode detector (SFD) for field size of 1×1, 2×2, and 3×3 cm<sup>2</sup> at depths of 1.5, 10 and 20 cm.

Field size (cm <sup>2</sup> )	Depth (cm)	EBT2±SD	PFD		EDGE		SFD	
			Penumbral width(mm) (80-20%)	Diff (EBT2-PFD) (mm)	Penumbral width(mm) (80-20%)	Diff (EBT2-EDGE) (mm)	Penumbral width(mm) (80-20%)	Diff (EBT2-SFD) (mm)
1×1	1.5	2.19±0.07	2.3	-0.11	2	0.19	1.9	0.29
	10	2.40±0.05	2.55	-0.15	2.35	0.05	2.1	0.3
	20	2.52±0.11	2.75	-0.23	2.6	-0.08	2.35	0.17
2×2	1.5	2.40±0.05	2.45	-0.05	2.15	0.25	1.95	0.45
	10	2.75±0.16	2.8	-0.05	2.6	0.15	2.4	0.35
	20	2.87±0.19	3.15	-0.28	2.9	-0.03	2.85	0.02
3×3	1.5	2.52±0.11	2.52	0	2.2	0.32	2.05	0.47
	10	2.87±0.11	2.95	-0.08	2.75	0.12	2.7	0.17
	20	3.09±0.30	3.33	-0.24	3.2	-0.11	3.05	0.04

All in all, as shown in Table 5.2.3., compared with both types of films, penumbral widths measured by PFD has significant difference from field size of 1×1 cm<sup>2</sup> for all depths and field size of 2×2 cm<sup>2</sup> at only depth 20 cm. EDGE differs significantly only at shallower depths for all field sizes. But SFD has larger diverges dramatically for smaller field sizes.

In this study, the penumbra measurement of the Photon diode detector are wider than Edge detector for all field sizes and depths. It might be because of the inaccuracy of measurement of the penumbra due to volume averaging effect. The results are agreed with Kyung-Hwan Chang et al[11] who reported that the penumbra measured with Photon diode detector was wider than the penumbra from Edge detector for field size between 1x1 and 10x10 cm<sup>2</sup>.

When the penumbral widths were compared between SFD and EBT2, the results presented that the penumbral widths measured with EBT2 are wider than those measured with SFD. The results are similarly to Jose M. Larraga-Gutierrez et al [7] who reported that the penumbral width from Gafchromic EBT2 film measurement were larger than the penumbral width from SFD diode measurement for all circular collimator diameters of 4, 6, 7.5, 10, 12.5, 15, 17.5 and 20 mm.

EDGE obtained comparable penumbral width compared with EBT 2 film. It supposed to have the thinnest penumbral width because it has the smallest sensitive volume. However EDGE showed bigger penumbral width than that of SFD, it might because EDGE has large external dimension. Nevertheless its external material made of brass (high density) which making shorter electron range. That is why its penumbral width is not too big and not too small. Hun-Joo Shin et al [30] reported that the beam profile simulated by GEANT4 Monte Carlo better matched to the EDGE than the PTW60017 shielded diode detector for small fields. Consequently, EDGE might seem promising to be a detector of choice for small field dosimetry

All in all, the penumbral width measured from various diode detectors obtain comparable results with those measured both using EDR2 radiographic and EBT2 radiochromic film within  $\pm 0.5$  mm.

## CHAPTER VI

### CONCLUSION

Penumbral widths for field size of  $1 \times 1$ ,  $2 \times 2$ , and  $3 \times 3$  cm<sup>2</sup> at depths of 1.5, 10, and 20 cm were measured at the small field conditions. Films (EDR2 and EBT2) were used as a reference penumbral width measurement to compare with diodes detectors (PFD, EDGE, and SFD).

EDR2 has slightly energy dependence compared with EBT2 film. It obtained wider penumbral width than EBT2 however there is no significant difference between them. PFD has widest penumbral width when compared with other diodes and EBT2. EDGE obtains comparable penumbral width and SFD show the thinnest penumbral width. However, the penumbra width measurement from various diode detector obtain comparable penumbra when compare with EBT2 radiochromic film. Over all, the results found that they are different within  $\pm 0.5$ mm.

Yin *et al* mentioned that SFD and the mini-ion-chamber are reliable and suitable for small field dosimetry because their detector sizes are smaller than measured field size larger than 5 mm by using Monte Carlo simulation suggested by Bjarngard *et al.* [26,27] Our smallest field size is  $1 \times 1$  cm<sup>2</sup> therefore our dedicated diodes (SFD and EDGE detectors) are considered the appropriate detectors of choice for penumbral width measurement in our measured small field sizes ranged between  $1 \times 1$  and  $3 \times 3$  cm<sup>2</sup>.

#### Further study

Laub and Wong suggested that diamond was suitable for small field dosimetry due to its high spatial resolution and water equivalent material [9]. Therefore this work might continue to explore by comparing with diamond detector and go smaller field size than  $1 \times 1$  cm<sup>2</sup> in order to investigate the accuracy of penumbral width measurement in stereotactic radiotherapy technique.

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**APPENDICES**

## APPENDIX A

**Table 1a** The pixel value and radiation dose of EDR2 film for created the calibration curve of field size  $1 \times 1 \text{ cm}^2$  at depth 1.5, 10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	4754	0	4901	0	4862
6.85	5204	7.76	5324	8.99	5499
19.58	6026	22.72	6481	26.67	6878
25.46	6403	29.92	7077	35.66	7594
63.64	9247	74.80	10652	89.29	12237
89.10	11498	105.28	12892	124.95	15562
101.82	12799	120.24	14681	142.92	16858
108.68	13087	127.44	15594	151.62	17365
114.55	14026	135.20	16236	160.61	19133

**Table 2a** The pixel value and radiation dose of EDR2 film for created the calibration curve of field size  $2 \times 2 \text{ cm}^2$  at depth 1.5, 10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	4898	0	4689	0	4888
6.39	5363	7.43	5224	8.88	5540
19.17	6266	22.30	6363	26.64	6949
25.56	6615	29.74	6896	35.85	7514
63.90	10112	74.97	11125	89.14	12521
89.46	11813	104.70	13467	124.99	15504
102.24	13173	120.19	15025	142.75	17173
108.63	13826	127.63	15890	151.63	18023
115.02	14400	135.06	16197	160.51	19574

**Table 3a** The pixel value and radiation dose of EDR2 film for created the calibration curve of field size  $3 \times 3 \text{ cm}^2$  at depth 1.5, 10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	4753	0	4774	0	4967
6.52	5367	7.19	5337	8.95	5755
19.57	6328	22.23	6338	26.84	6799
25.01	6870	30.08	7145	35.79	7659
64.16	10123	75.20	10848	89.14	12320
89.17	12019	105.28	13383	124.93	15910
102.22	13278	120.32	15155	142.83	17410
108.75	13357	127.51	15600	151.77	18007
115.27	14734	134.71	16131	160.72	19409

## APPENDIX B

**Table 1b** The pixel value and radiation dose of GafChromic<sup>®</sup>EBT2 film for created the calibration curve of field size 1×1 cm<sup>2</sup> at depth 1.5,10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	2959	0	2936	0	2954
6.85	3076	7.76	3243	8.99	3279
19.58	3526	22.72	3669	26.67	3829
25.46	3683	29.92	3838	35.66	4063
63.64	4525	74.80	4873	89.29	5366
89.10	5731	105.28	6177	124.95	6631
101.82	5987	120.24	6504	142.92	6959
108.68	6079	127.44	6635	151.62	7184
114.55	6110	135.20	6658	160.61	7307

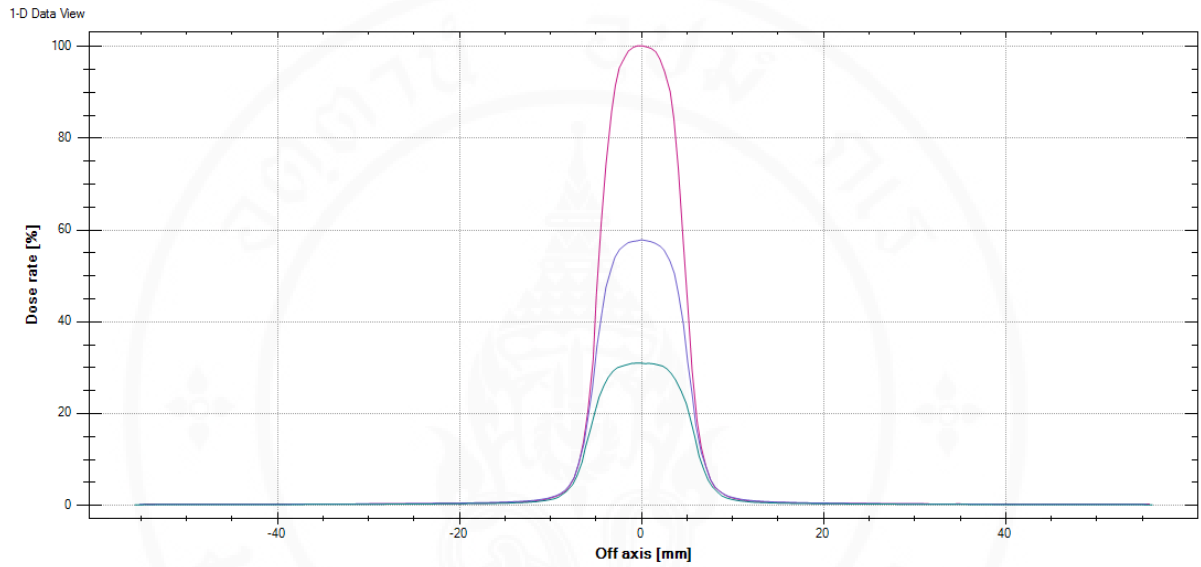
**Table 2b** The pixel value and radiation dose of GafChromic®EBT2 for created the calibration curve of field size  $2 \times 2 \text{ cm}^2$  at depth 1.5, 10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	2965	0	2908	0	2973
6.39	3132	7.43	3155	8.88	3293
19.17	3570	22.30	3667	26.64	3915
25.56	3682	29.74	3780	35.85	4052
63.90	4648	74.97	4848	89.14	5356
89.46	5857	104.70	6154	124.99	6582
102.24	6102	120.19	6391	142.75	6922
108.63	6146	127.63	6615	151.63	7057
115.02	6232	135.06	6713	160.51	7104

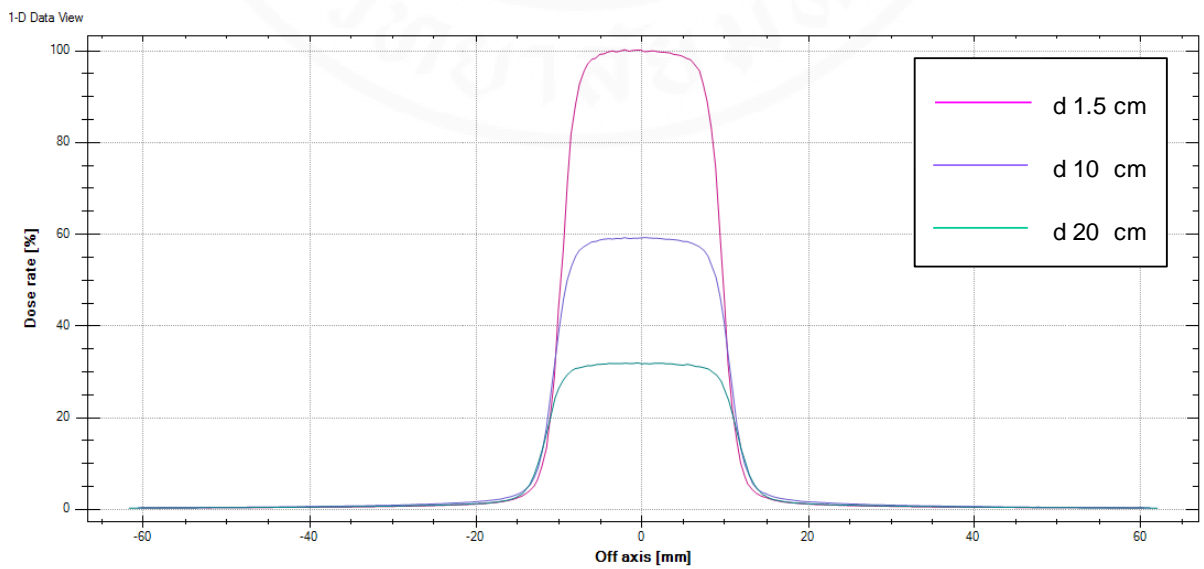
**Table 3b** The pixel value and radiation dose of GafChromic®EBT2 for created the calibration curve from of field size  $3 \times 3 \text{ cm}^2$  at depth 1.5, 10 and 20 cm

Depth 1.5 cm		Depth 10 cm		Depth 20 cm	
Dose(cGy)	Pixel value	Dose(cGy)	Pixel value	Dose(cGy)	Pixel value
0	2921	0	2941	0	2996
6.52	3153	7.19	3161	8.95	3346
19.57	3558	22.23	3693	26.84	3846
25.01	3685	30.08	3858	35.79	4016
64.16	4664	75.20	4923	89.14	5265
89.17	5868	105.28	6217	124.93	6614
102.22	6166	120.32	6490	142.83	7086
108.75	6265	127.51	6510	151.77	7277
115.27	6302	134.71	6628	160.72	7283

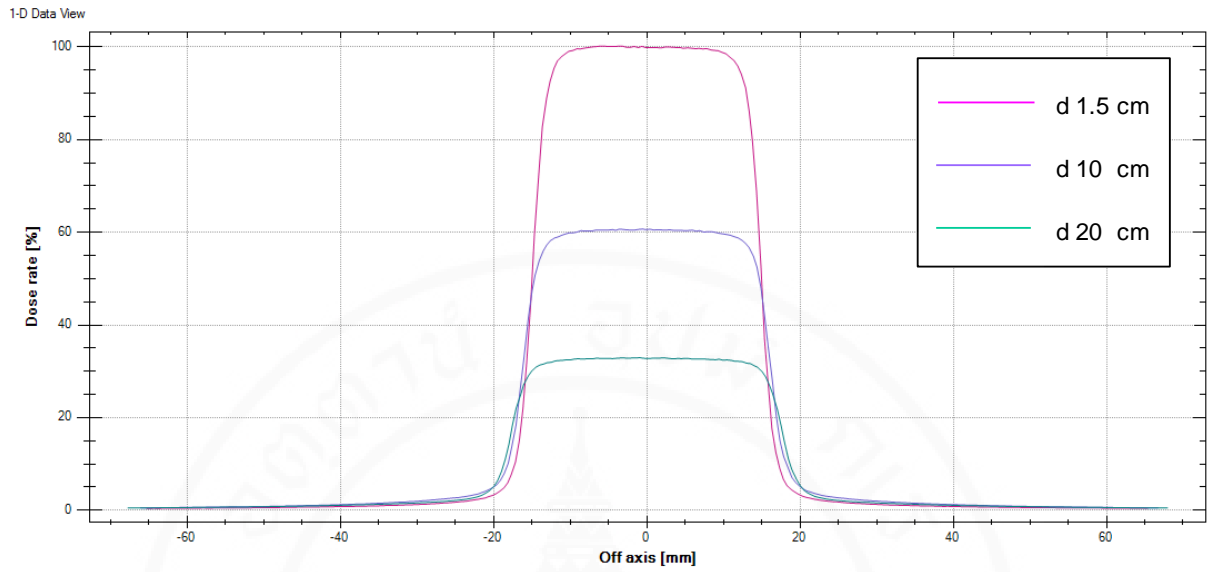
### APPENDIX C



(a) field size  $1 \times 1 \text{ cm}^2$

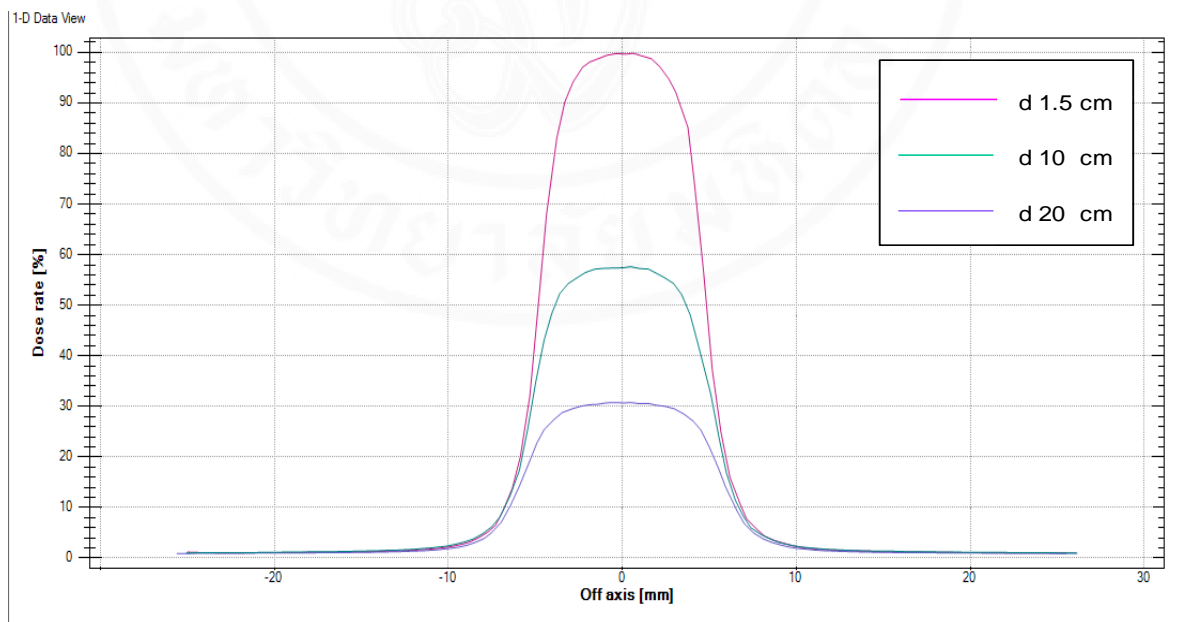


(b) field size  $2 \times 2 \text{ cm}^2$



(c) field size  $3 \times 3 \text{ cm}^2$

Figure 1c(a-c) Beam profile measurement for field size of  $1 \times 1, 2 \times 2$  and  $3 \times 3 \text{ cm}^2$  using Photon diode detector



(d) field size  $1 \times 1 \text{ cm}^2$

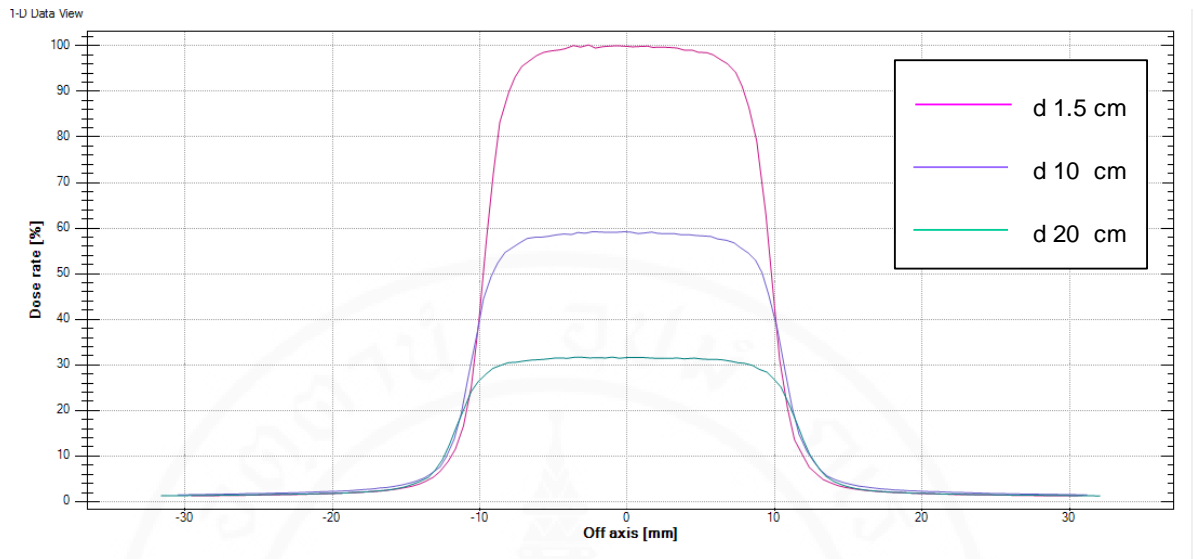
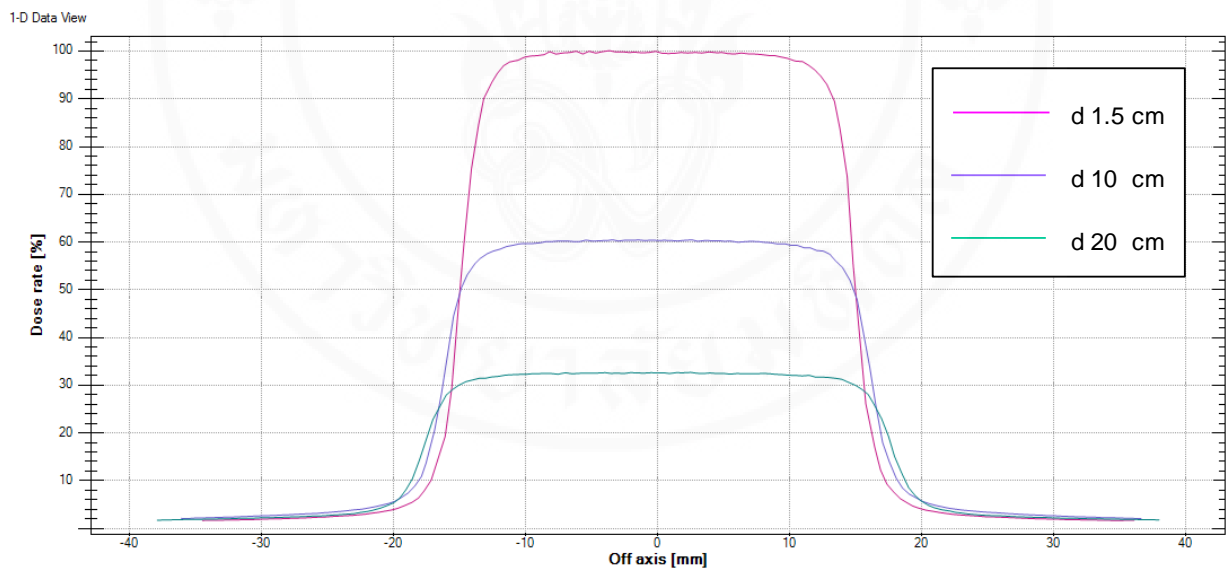
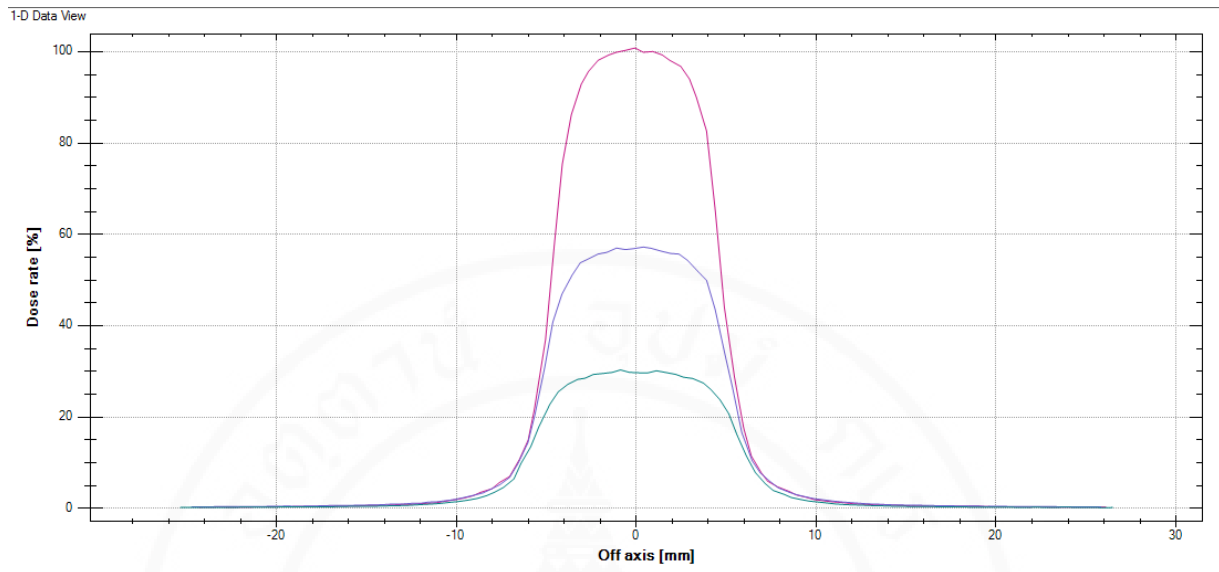
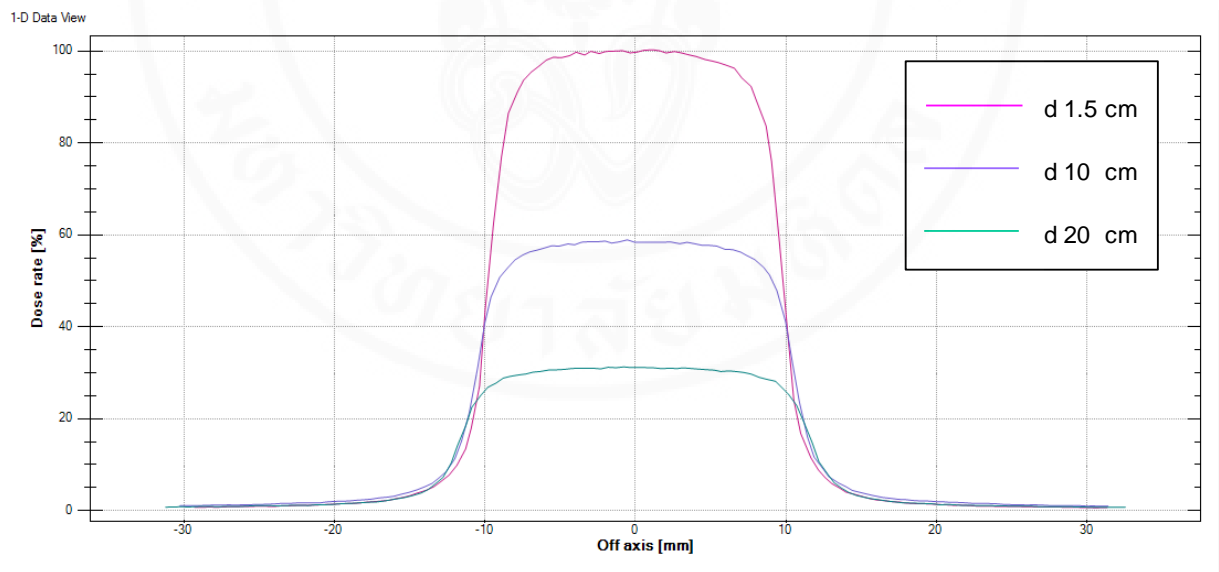
(e) field size  $2 \times 2 \text{ cm}^2$ (f) field size  $3 \times 3 \text{ cm}^2$ 

Figure 2c(d-f) Beam profile measurement for field size of  $1 \times 1, 2 \times 2$  and  $3 \times 3 \text{ cm}^2$  using EDGE detector.



(g) field size 1×1cm<sup>2</sup>



(h) field size 2×2cm<sup>2</sup>

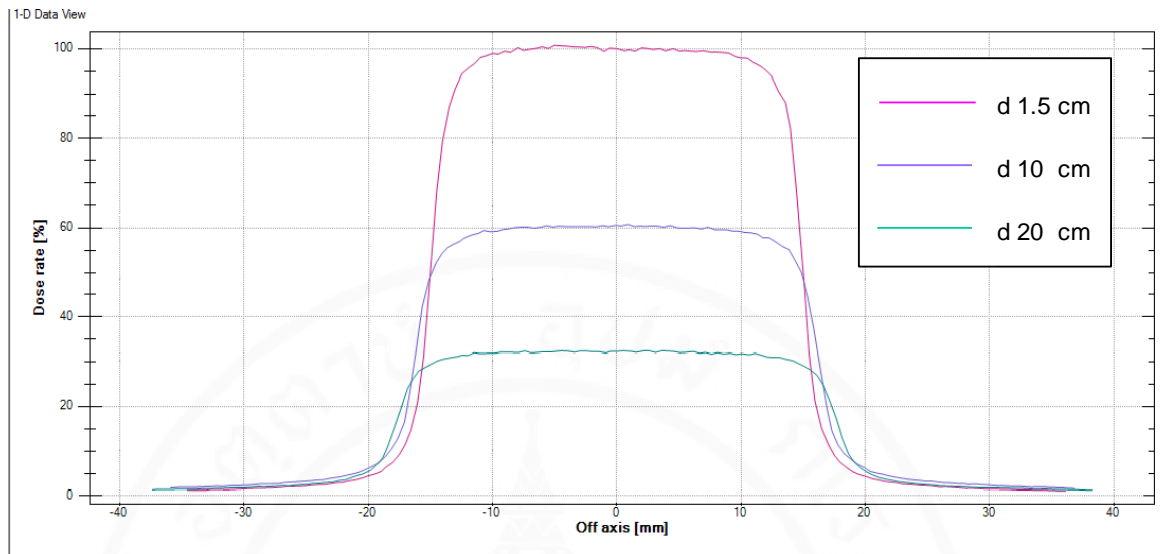
(i) field size 3×3 cm<sup>2</sup>

Figure3c(g-i) Beam profile measurement for field size of 1×1, 2×2 and 3×3 cm<sup>2</sup> using Stereotactic diode detector

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