MEASUREMENT OF RADIATION EXPOSURE IN DIAGNOSTIC X-RAY ENERGY RANGE USING PHOTOSTIMULABLE PHOSPHOR PLATE

WIWAT OWASIRIKUL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (RADIOLOGICAL TECHNOLOGY) FACULTY OF GRADUATE STUDIES MAHIDOL UNIVERSITY 2008

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Thesis
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MEASUREMENT OF RADIATION EXPOSURE IN DIAGNOSTIC X-RAY ENERGY RANGE USING PHOTOSTIMULABLE PHOSPHOR PLATE

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ABSTRACT

The purpose of this study was to examine a method using a photostimulable phosphor plate (PSP plate) of computed radiography (CR) system as a detector for exposure measurement under x-ray beam at potential voltages from 40 to 120 kVp. A pixel value (PV) of the exposed PSP was converted to exposure using Fuji's equation and compared with the exposure measured from a calibrated 6 cc ionization chamber. The factors affecting the PSP plate such as fading, cassette, PSP size, exposed area and selected region of interest (ROI) area were also investigated.

The results showed that the fading effect of the PV reading was less than 3% within 10 minutes after irradiation. The PV reading of the PSP exposed without cassette was lower than the reading with a cassette by approximately 1%. As a result, the exposure calculated of the PSP exposed without cassette was lower by about 9%. At a fixed exposed area the PV was slightly decreased with increasing the ROI area selected. As a result, the exposure calculated was slightly decreased while the ROI area selected was increased. Compared to the ionization chamber, the exposure calculated of small PSP size without cassette with ROI area selected of 80% of exposed area showed the best agreement and indicated lower exposure at low kVp but slightly higher at high kVp.

The radiation exposure calculated from the PV depends on the ROI area selected and some kVps. The dosimeter using the small PSP size without cassette, selection of ROI area at 80% of exposed area and multiplication of correction factor for energy dependence can measure radiation exposure from 40 to 120 kVp x-ray beam within an accuracy ±4% of ionization chamber.

KEY WORDS: COMPUTED RADIOGRAPHY / PHOTOSIMULABLE PHOSPHOR - PLATE / RADIATION EXPOSURE / PIXEL VALUE

51P.

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การวัดปริมาณรังสีในช่วงพลังงานเอกซเรย์วินิจฉัย โดยอาศัยแผ่นเรืองแสงชนิดกระตุ้นด้วยแสง (MEASUREMENT OF RADIATION EXPOSURE IN DIAGNOSTIC X-RAY ENERGY RANGE USING PHOTOSTIMULABLE PHOSPHOR PLATE)

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บทคัดย่อ

ในการศึกษาครั้งนี้ ได้ทำการศึกษาวิธีการใช้แผ่นรับภาพของเครื่องถ่ายภาพทางรังสีระบบคอมพิวเตอร์เป็นเครื่องมือวัดปริมาณรังสีเอกซเรย์ในช่วงความต่างศักย์ตั้งแต่ 40 ถึง 120 กิโลโวลต์ ค่าพิกเซลของแผ่นรับภาพถูกคำนวณเป็นปริมาณรังสีโดยใช้สมการของบริษัทฟูจิ และเปรียบเทียบกับเครื่องมือวัดรังสีชนิดแตกตัวเป็นประจุขนาด 6 ซีซี นอกจากนี้ยังได้ศึกษาปัจจัยอื่น ๆ ที่มีผลกระทบกับการใช้แผ่นรับภาพเช่น การสูญหายของค่าพิกเซล ผลกระทบจากคาสเซทที่มีต่อค่าพิกเซล พื้นที่ฉายรังสี และพื้นที่เลือกค่าพิกเซลอีกด้วย

จากการศึกษาพบว่า การสูญหายของค่าพิกเซลน้อยกว่า 3 เปอร์เซ็นต์ในเวลา 10 นาที หลังจากแผ่นรับภาพถูกฉายรังสี ค่าพิกเซลของแผ่นรับภาพชนิดไม่มีคาสเซทมีค่าน้อยกว่าชนิดมีคาสเซทประมาณ 1 เปอร์เซ็นต์ ส่งผลให้ปริมาณรังสีที่คำนวณได้ของแผ่นรับภาพชนิดไม่มีคาสเซทมีค่าน้อยกกว่าชนิดมีคาสเซทประมาณ 9 เปอร์เซ็นต์ เมื่อพื้นที่ฉายรังสีคงที่จะพบว่า ค่าพิกเซลลดลงเล็กน้อยเมื่อพื้นที่เลือกค่าพิกเซลมากขึ้น ส่งผลให้ค่าปริมาณรังสีที่คำนวณได้มีค่าลดลงเล็กน้อยตามไปด้วย เมื่อเปรียบเทียบกับเครื่องมือวัดรังสีชนิดแตกตัวเป็นประจุพบว่า ค่าปริมาณรังสีที่คำนวณได้จากการเลือกค่าเฉลี่ยพิกเซลที่ 80 เปอร์เซ็นต์ของพื้นที่ฉายรังสี ของแผ่นรับภาพขนาดเล็กชนิดไม่มีคาสเซทมีค่าใกล้เคียงมากที่สุด และมีค่าลดลงที่พลังงานเอกเรย์ต่ำแต่สูงขึ้นเล็กน้อยที่พลังงานเอกซเรย์สูง

ค่าปริมาณรังสีที่คำนวณได้จากค่าพิกเซลขึ้นอยู่กับพื้นที่เลือกค่าพิกเซลและพลังงานบางช่วงของรังสีเอกซเรย์ การเลือกใช้แผ่นรับภาพขนาดเล็กชนิดไม่มีคาสเซทกับการเลือกค่าเฉลี่ยพิกเซลที่ 80 เปอร์เซ็นต์ของพื้นที่ฉายรังสี และการคูณด้วยค่าแก้พลังงานรังสีแล้ว พบว่าสามารถนำมาใช้วัดปริมาณรังสีเอกซเรย์ในช่วงความต่างศักย์ตั้งแต่ 40 ถึง 120 กิโลโวลต์ ภายใต้ความถูกต้อง 4 เปอร์เซ็นต์เมื่อเทียบกับเครื่องมือวัดปริมาณรังสีชนิดแตกตัวเป็นประจุ

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LIST OF ABBREVIATIONS

Abbreviations	Term
Ba	Barium
Br	Bromine
C	Column
Cs	Cesium
Cl	Chlorine
CF	Correction factor
CR	Computed radiography
CT	Computed tomography
DICOM	Digital imaging and communications in medicine
eV	Electron volt
E	Exposure
EDR	Exposure data recognizer
EI	Exposure index
Eu	Europium
F	Fluoride
FDD	Focal detector distance
FWHM	Full width at half maximum
HVL	Half value layer
IC	Ionization chamber
IP	Imaging plate
kVp	Kilo-voltage peak
lp	Line pair
L	Latitude
m	Meter
mAs	Milli-ampere second
Pa	Pascal

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LIST OF ABBREVIATIONS (CONTINUED)

Abbreviation	Term
PMT	Photomultiplier tube
PV	Pixel value
PSL	Photostimulated luminescence
PSP	Photostimulable phosphor
R	Roentgen
Rb	Rubidium
ROI	Region of interest
s	Second
S	Sensitivity
SAL	Scan average level
SID	Source image distance
Sr	Strontium
Tl	Thallium

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CHAPTER I
INTRODUCTION

The trend in diagnostic radiology is away from imaging systems that use analog screen-film toward ones that incorporate digital detectors. Computed radiography (CR) is the most common digital radiography modality in radiology departments today, with an estimated 7000 systems in use worldwide (1). CR uses photostimulable phosphor (PSP) device as direct digital capture of projection radiographs. The photostimulable phosphor (PSP) device may be called commercially either PSP screen or imaging plate (IP). The fundamental innovation in the development of CR was by Kodak (2) who conceived the storage of an x-ray image in a phosphor screen. The significant technical steps and conceptualization of application was recognized by Fuji (3) to produce the first medical x-ray images. Fuji, the main developer of CR in the eighties, used $BaFBr:Eu^{2+}$ phosphor and a cassette-based approach. During this time, Agfa and Kodak performed research and development on the same method.

In this era the phosphors were used most often in the barium fluorohalide family in powder form and deposited onto a substance to form an imaging plate or screen. X-ray absorption mechanisms are identical to those of conventional phosphor screens used with film. They differ in that the useful optical signal in not derived from the light emitted in prompt response to the incident radiation, but rather from subsequent emission when the latent image, consisting of trapped charge, is optically stimulated and released from metastable traps. This process is called photostimulated luminescence (PSL) resulting in the emission of shorter wavelength (blue) light in an amount proportional to the original x-ray irradiation. A comprehensive review of the types, development and operation of PSPs used in CR can be seen in Rowlands JA, 2002 (4).

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A general type of CR system is the cassette-based system as shown in figure 1.1 where a PSP containing the storage phosphor is positioned in a light-tight enclosure or cassette, exposed to the x-ray image and then read out by raster scanning with a laser to release the PSL. The blue PSL light is collected with a light guide and detected with a photomultiplier tube (PMT). The PMT signal is digitized to form the image on a point-by-point basis (5).

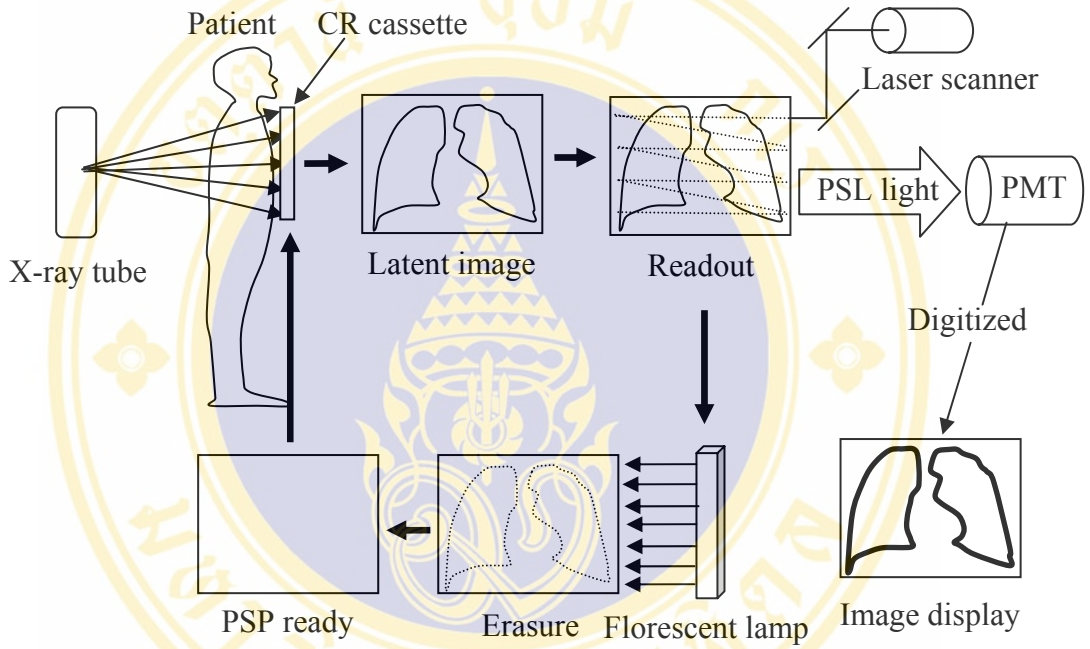

Figure 1.1 Overall concepts of general CR systems. Cassette-based requiring carries cassette back and forth between the x-ray and readout system.

The recent typical PSPs used in the most commercial IP systems are shown in table 1.1. The physical properties of PSPs including the average energy W, which must be absorbed to release a single light photon, and wavelength λ of the light emitted by the activator have been listed. Z is the atomic number of the radiologically important, i.e. heavy element or elements, E_k is K-absorption edge energy of the heavy elements, E_g is the energy gap of the host crystal in electron volts (eV), density is quoted for a single crystal, i.e. 100% packing factor, G = conversion gain (emitted light photons per 50 keV of absorbed x-ray energy). For the photostimulable phosphors the PSL light is obtained when the trapped energy is fully stimulated. Decay time constants are usually the same whether the light is given promptly on

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stimulation by x-rays or after stimulation of trapped charge by a laser since they are limited by characteristics of the same luminescence center and not the trapping, and release mechanisms. A notable feature is that the conversion gain G, for the PSPs is an order of magnitude smaller than that for conventional phosphors.

Table 1.1 Physical properties of some PSPs and conventional phosphors (4).

Phosphor	Z	E_k (keV)	E_g (eV)	Density (gcm^{-3})	W (eV)	G (photons/ 50 keV)	Decay time (ms)	Light emission peck (nm)	Spectrum for stimulation (nm)
BaFBr:Eu^{2+}	56	37.4	8.3	5.1	360	140	0.7	390	500-650
CsBr:Eu^{2+}	55	36	7.3	4.45	250	200	0.7	440	685
RbBr:Eu^{2+}	37/ 35	15.2/ 13.4	-	3.35	-	-	0.35	433	735

It is known that the amount of photostimulated luminescence (PSL) emitted from the IP is linearly proportional to the exposure over four orders of magnitude (6). As a result, each CR manufacturer defines their exposure index as it is related to PSL intensity. Fuji IPs use a sensitivity number, S, as the exposure index where S = 200/Exposure (mR) (7). Kodak IPs use an exposure index, EI, where EI = 1000 x log (exposure in mR) + 2000 (8). Agfa IPs set an exposure related to a log of median value of the histogram, called lgM, and the scan average level, SAL (1). The relationship of the amount of exposure received by the IP as it is related to the exposure index will be described in some details in the chapter 3.

According to the exposure relationship, there are some papers (9-14) that have been recently reported of using PSP for estimating the exposure with indices relating to the PSL value. Most of them estimated the exposure via the S value (9-13). Only Lui et al, 2005 (14) reported the procedure for using a Fuji IP for the measurement of Computed Tomography (CT) radiation profiles via the pixel values. The pixel value is the digital value converted from the amount of PSL light emitted from the IP irradiated. Therefore it is directly related to the amount of radiation absorption in the PSP at each pixel itself.

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In this study we examined how PSP can be utilized to accurately measure the exposures from the x-ray beam at the range of 40 to 120 kVp via the pixel values. The objectives will be fully described in the chapter 2. The method and materials, results and discussion will be described in the chapter 4, 5 and 6 respectively.

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CHAPTER II
OBJECTIVES

The purposes of this study are as the following.

1. To study a method of using a PSP plate of computed radiography system as a detector for dosimetric measurements of x-ray beam at the tube voltage from 40 to 120 kVp.
2. To find out the factors affecting of the using PSP plate on the measurement of x-ray exposures.
3. To access the limitation and suggestion involved the using PSP plate for dosimetric measurements.

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CHAPTER III
LITERATURE REVIEWS

This chapter reviews a number of theoretical and experimental methods available for measurement of radiation exposure using PSP plate of computed radiography as a detector.

3.1 Photostimulable phosphors

The photostimulable phosphor first used for CR was BaFBr:Eu^{2+}. It is a layered structure that gives rise to phosphor grains with a plate-like rather than the more desirable cubic morphology. BaFBr:Eu^{2+} can store a latent image for 8 hours after irradiation (15). In recent years most manufacturers have used $BaFBr_{0.85}I_{0.15}$:Eu^{2+} not for the increasing in x-ray absorption compared to BaFBr:Eu^{2+}, but rather for the better optical match of wavelength of stimulation of the phosphor to diode lasers. Recently Konica has utilized pure BaFI:Eu^{2+} in commercial systems (16) where the change in absorption is significant. RbBr:Tl^{+} is cubic and has the advantage that it can be made into a needle-structured layer. By guiding the light to the surface can achieve high resolution. However it has the disadvantage of a rapid loss of the latent image that makes it unsuitable for cassette-based systems. Konica has used this material in integrated readers where the CR plate can be rapidly read out in situ immediately after the termination of the exposure. CsBr:Eu^{2+} is also cubic, can be made in the needle structure, has a stable latent image and can be photostimulated. Agfa has proposed using this material in both cassette-based and integrated readers (17).

3.2 Relationship between pixel value and exposure

It is widely believed that over the range of clinical imaging conditions the pixel value produced by a PSP plate is uniquely determined by x-ray exposure incident upon the receptor at that pixel's location. Several investigators have empirically

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derived a correlation between pixel value and the exposure incident on the detector (18-20).

The PSP plate is an energy-integrating detector. The energy deposited in the PSP depends on the x-ray energy absorption characteristics of the phosphor and the spectrum of the incident x-ray beam. Since the attenuation and energy absorption vary with photon energy, both beam quality and exposure must be affect to predict pixel values (9).

The Fuji device pixel readout amplification is controlled by two parameters; the sensitivity (S) controls the pixel value read amplifier gain and the latitude (L) controls slope of the amplifier response. The exposure relates with specific factor or L and S value that also relates with pixel value. This relationship can be expressed as this following.

$$PV = \frac{1024}{L}\log_{10}(k \cdot S \cdot E) + 511 \qquad (3.1)$$

where PV is the pixel value [unit less]

E is the exposure [mR]

L is the system read latitude [unit less]

S is the system read sensitivity [mR^{-1}]

k is the constant value [unit less]

The pixel value can be converted to the exposure by taking logarithm based 10 in both sides of equation. Then, arrangement of equation is performed as shown in this following.

$$E = \frac{10^{L/1024(PV-511)}}{S \cdot k} \qquad (3.2)$$

From Eq. (3.2) the exposure therefore can be calculated from the pixel value. The pixel value commonly shows on diagnostic monitoring in clinical image and it is

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direct proportion to the exposure. Therefore, the pixel value of the PSP plate probably measures the radiation exposure.

Tucker DM, 1997(9) investigated the relationship between x-ray photon energy and pixel value. They created a calculated pixel value as a function of exposure similar to an exponential function (20). The calculated exposure compared with measured pixel value those as functions of photon energy and beam quality. Experiments were performed at x-ray potential voltage range from 60 to 120 kVp with 0.53 added filtration increments. The 35x43 cm Fuji PSP plate was uniformly exposed with ionization chamber measurement at source image distance (SID) greater than 190 cm. The IP was processed in fixed mode (S = 200, L = 4). The raw pixel data were printed to 25x35 cm and then transferred electronically from the PSP reader to minicomputer with KHOROS software. A region of interest (ROI) of 8x8 cm^2 was identified in the center for average pixel value measured. They found the measured pixel value and the calculated pixel value less accurately at low kVp and high HVLs investigated. The pixel value calculated agreed with ±5% of measured pixel values over the range of beam energies, exposures and qualities. Therefore, they concluded that x-ray beam quality and beam energy significant effected on the pixel value.

Liu HL, 2005 (14) used a STVI-Fuji PSP plate for measure CT radiation beam profile. The aims studied the proper exposure and processing conditions of the IP and then compared CT radiation beam profile in terms of full width at half maximum (FWHM) with digitized film dosimeter. The pixel value was converted to exposure using exposure equation of Fuji as shown in Eq. (3.2) with the constant k value of 0.005. A single 25 cm x 30 cm of the PSP plate and a XV ready-pack film were used. The PSP plate and the film were exposed by x-ray tube voltage at 80 kVp and mAs from 5 to 80 mAs with 10x10 cm^2 field size. The PSP plate was processed in CR reader with different Fixed EDR mode with L = 1 and 4 and S = 5, 50, 200. They also examined the exposed PSP plate with and without cassette. Two image receptors were exposed in 5 mm, 10 mm and 15 mm collimation of 16 multislice CT scanner. They found that the PSP plate generated similar profile to digitized film except at the profile edge. The pixel value of PSP plate exposed with cassette was slightly lower

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than without cassette but the FWHM measurements were exactly the same. They recommended using the PSP plate with cassette for measuring the CT radiation profile. They founded the beam profiles of overexposed PSP plate were flatter and wider plateaus than properly exposed profiles. They suggested the proper exposed and processed be used low S number and high L number due to the proper beam profiles. They concluded the IP successfully used to measure CT beam profile.

Recently Ariga E, 2007 (13) used Fuji PSP plate for exposure measured using the S values. They determined exposure inversely proportional to the S value. They also examined some characteristics of the PSP plate such as fading rate of PSL signals, dependency of exposure and beam quality on S number and accuracy of the PSP plate dosimeter. The 35x35 cm PSP plate with cassette was calibrated by using a 6 cc. ionization chamber as the same position. Each dosimeter was irradiated at x-ray tube voltage from 50 to 120 kVp and added filtration from 0 to 4.0 mmAl with field size of 8x8 cm^2. The ROI of 5x5 cm^2 was identified the S values. They found that the fading was negligible when the PSL signals of Fuji PSP plate exposed with cassette were read within 4 min after irradiation. The fading was shown less than 1.9% when it was normalized to 2 min after irradiation. The S values were used between 7 and 10000 with uncertainty of ±5% in all tube voltage and beam quality investigated. Therefore, they suggested the PSP plate can be estimated exposure under diagnostic x-ray beam energy.

In the last literature, the S values can be used estimated exposure. However, it is inconvenience in routine practice. In this study, the pixel value was used to calculate exposure using exposure equation and compared with reference dosimeter.

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CHAPTER IV
MATERIALS AND METHODS

4.1 MATERIALS

4.1.1 CR system

In this study, a CR system composed of an x-ray equipment (QUEST HF series, Quantum Medical imaging) as shown in figure 4.1 and a CR reader FCR XG-1 (Fuji Photo Film Co., Ltd.) as shown in figure 4.2. The x-ray equipment was calibrated with quality control tests (21) as shown results in table 4.1. Fuji CR reader has three EDR modes: auto, semi-auto and fixed modes. The auto mode implies the S and L values are automatically adjusted of histogram of clinical image of interest to provide optimum contrast and density. For semi mode, the L value is freezed where the S value can be adjusted. For fixed mode, it allows the user to specify the value of both L and S. The L value can be adjusted from 0.5 to 4 and the S value from 4 to 20000.

Table 4.1 Quality control tests for Quantum x-ray equipment.

Tests	Acceptable range	Results of testing
Collimator and beam alignment	x and y axis ≤ 2%FDD	x = 1.1% and y = 1.5%
Exposure time (ms)		5 ms; 5.48 x 10^{-5} (SD value) 50 ms; 5.48 x 10^{-5} (SD value) 100 ms; 8.94 x 10^{-5} (SD value)
Reproducibility	CV≤0.05	100 mA, 0.2 sec; CV=0.003 200 mA, 0.1 sec; CV=0.0034
Linearity	$\alpha<0.1$	$\alpha=0.007$

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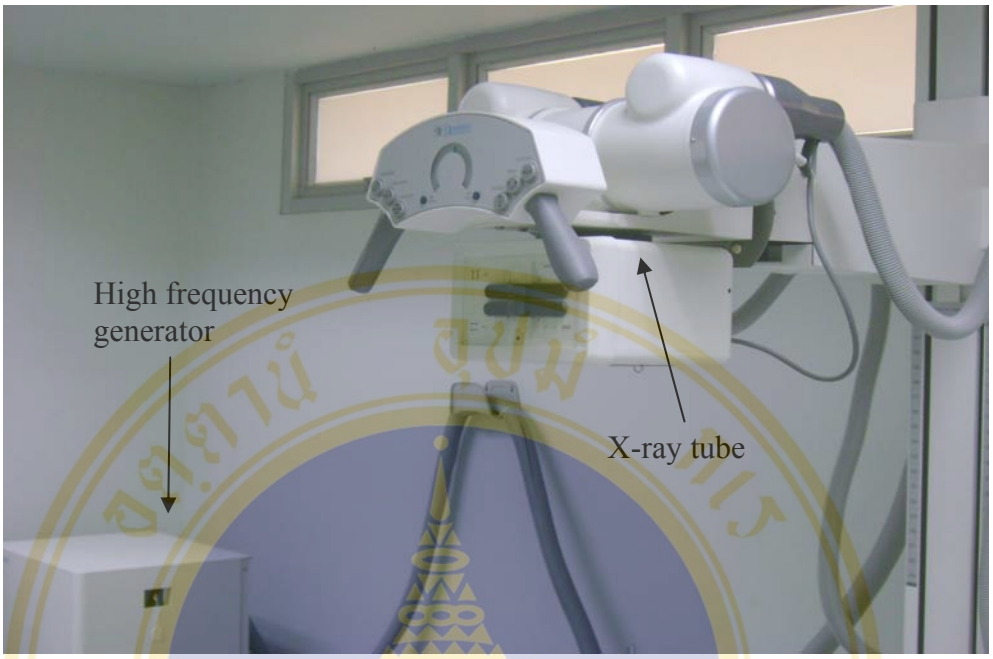

Figure 4.1 The Quantum x-ray equipment composed of a high frequency generator and an x-ray tube with 2.9 mmAl total filtration.

Figure 4.2 FCR XG-1 consists of a single PSP slot and CR console for operational control. There are three EDR modes for readout process called auto, semi, and fix modes.

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4.1.2 The PSP plate

In this study, the PSP plate ST-VN (Fuji Photo Film Co., Ltd.) sizes of 20x25, 35x35 and 35x43 cm (figure 4.3) were used. The characteristics of the PSP plates are shown in table 4.2.

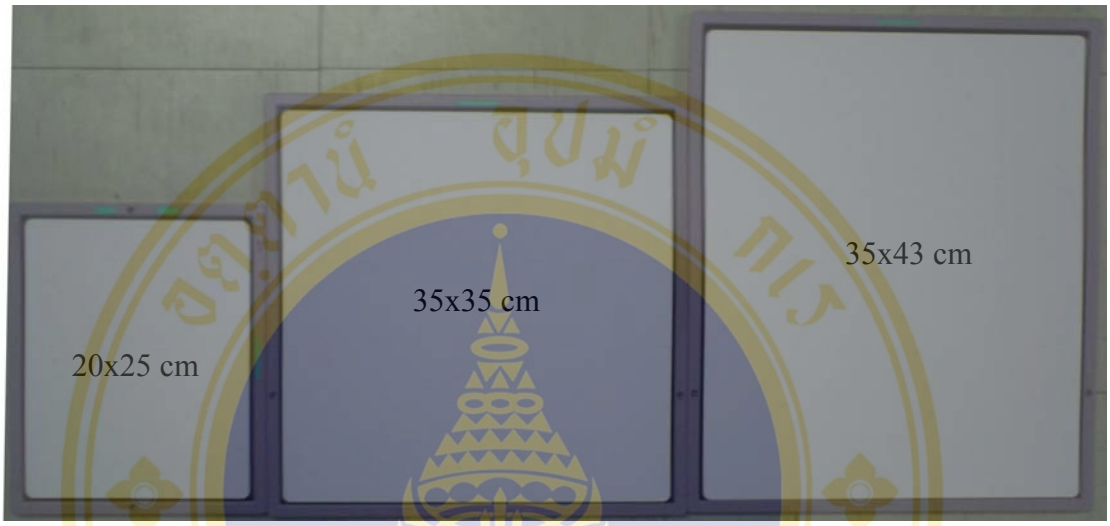

Figure 4.3 The ST-VN PSP plate and its cassette in specific sizes (a) 20x25 cm, (b) 35x35 cm and (c) 35x43 cm.

Table 4.2 Characteristics of ST-VN PSP plate sizes.

Size (cm x cm)	Pixel size (μm)	Resolution (lp/mm)
20x25	100	5.0
35x35	150	3.3
35x43	200	2.5

4.1.3 Ionization chamber dosimeter.

For all investigations, a calibrated 6 cc. ionization chamber Radcal 10X9-6 with electrometer model 9095 (Radcal Corporation) as shown in figure 4.4 was used as the standard dosimeter to employ the exposure measurement. The energy dependence from the x-ray energy of 30 keV to 150 keV is quoted to be less than ±3% for 10X9-6 chamber. The accuracy of dose measurement is ±4% of reading value at the condition temperature 15°c to 35°c and pressure 60 to 150 kPa (22).

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Figure 4.4 Ionization chamber (10X9-6) and electrometer model 9095.

4.1.4 Application programs

In this study, the application programs namely efilm program versions 1.7.1 (efilm Medical Inc., Toronto, Ontario, Canada) and MATLAB program versions 6.5 (The Math Works, Inc, Natick, MA) were used. The efilm program was used to manage and manipulate DICOM file images sending from CR reader to a personal computer on a diagnostic monitor. The MATLAB program was used to evaluate the average pixel value from measured pixel value on the DICOM image.

4.2 METHODS

4.2.1 Determination of the digital pixel value

After each the PSP plate was irradiated, it was carried to readout its signal with FCR reader. The DICOM file image was transferred to a diagnostic monitor by efilm program for management and manipulation. The digital pixel values were determined as the following procedures.

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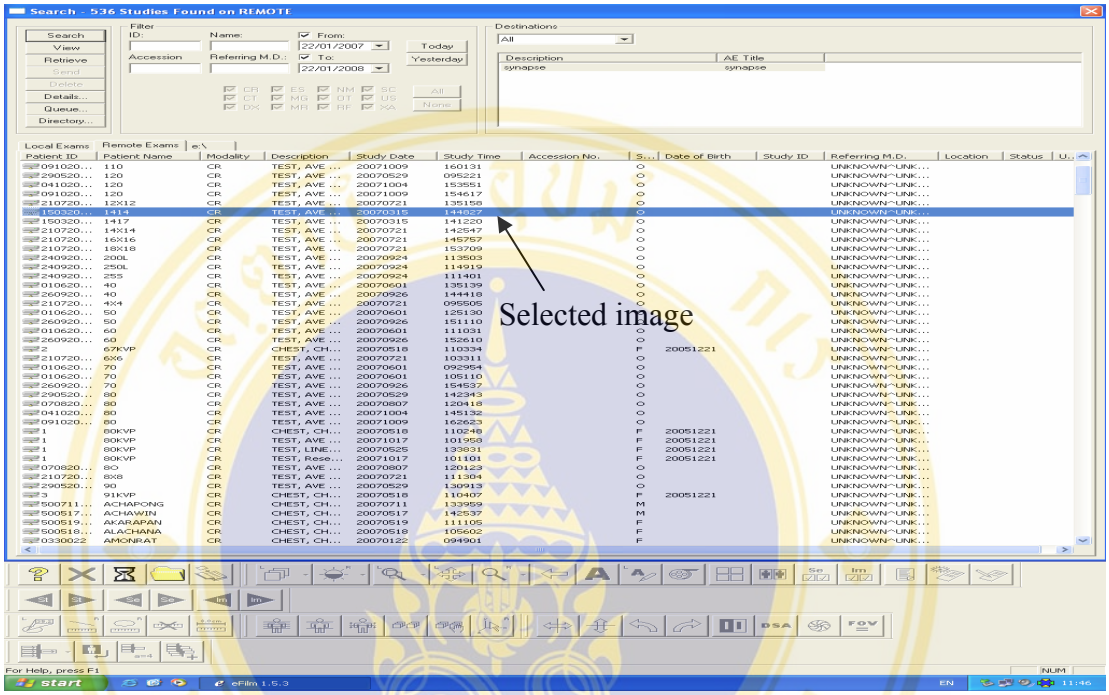
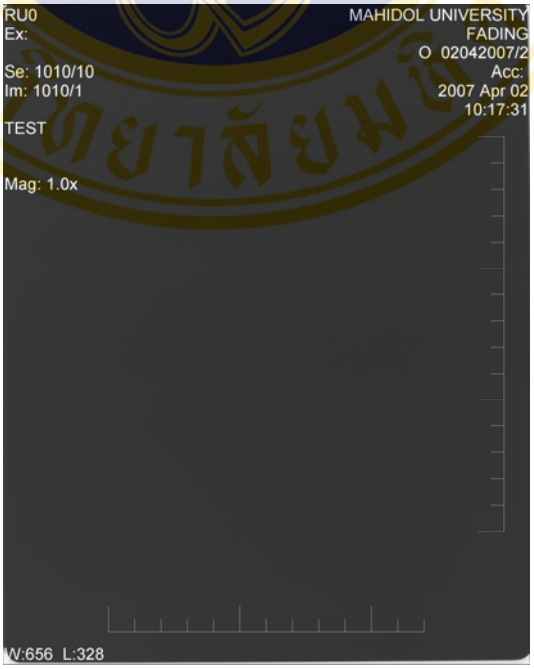
1. The efilm program version 1.7.1 was opened and then a DICOM image file was selected as the page shown in figure 4.5 (a). The selected DICOM image would appear on the diagnostic monitor as in figure 4.5 (b).



(a)



(b)

Figure 4.5 (a) the front page of efilm and DICOM image file selected. (b) The selected image on the diagnostic monitor.

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2. The MATLAB program version 6.5 was opened and then the source code (see appendix A) for evaluation of pixel value from DICOM image was entered as the page shown in figure 4.6.

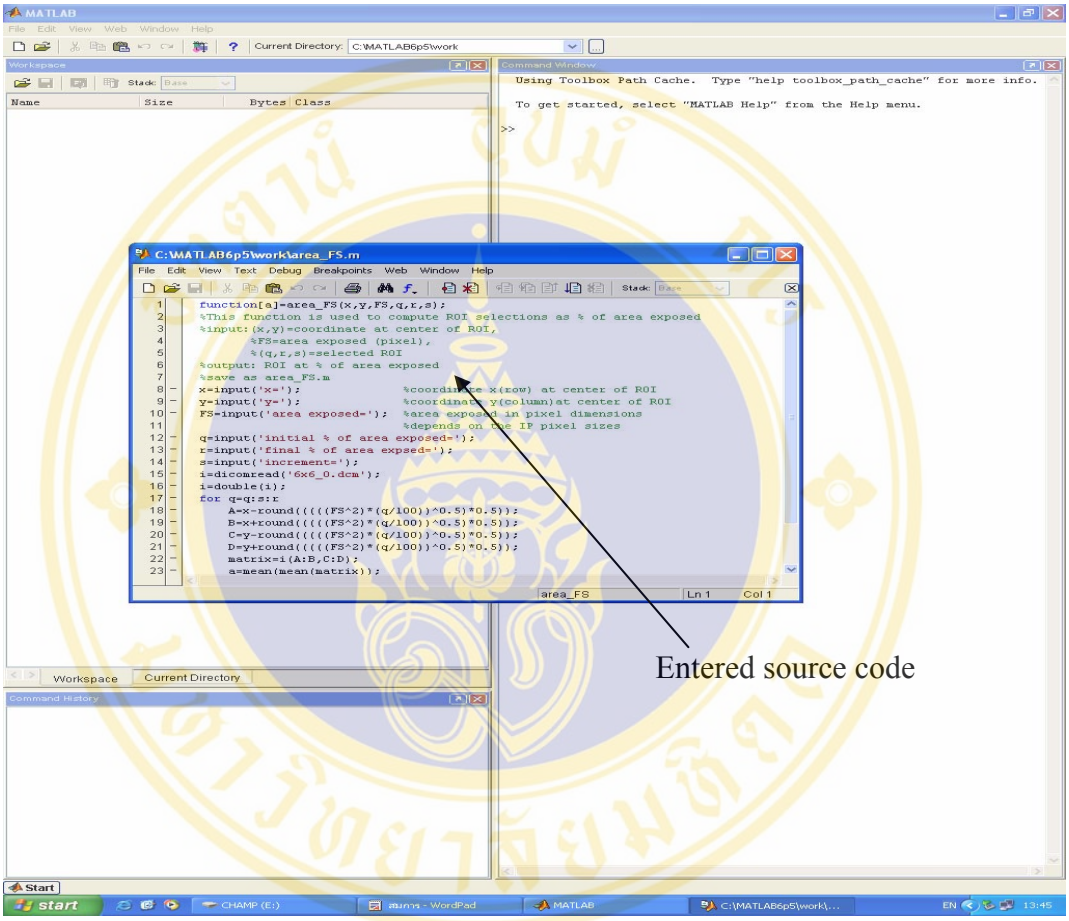

Figure 4.6 The page of MATLB with entered source code.

3. The average pixel value from the selected DICOM image was determined by selected a ROI (region of interest) on the image as seen in figure 4.7(a) for selected ROI as a percentage of exposed area and (b) for selected ROI as a PSP plate pixel size at the center of exposed area. The values of exposed area, ROI area as a percentage of exposed area, and the position of the center pixel of ROI area in terms of a coordinate (x,y) were entered into MATLAB (see also in figure 4.6). The average pixel value would be automatically showed on screen.

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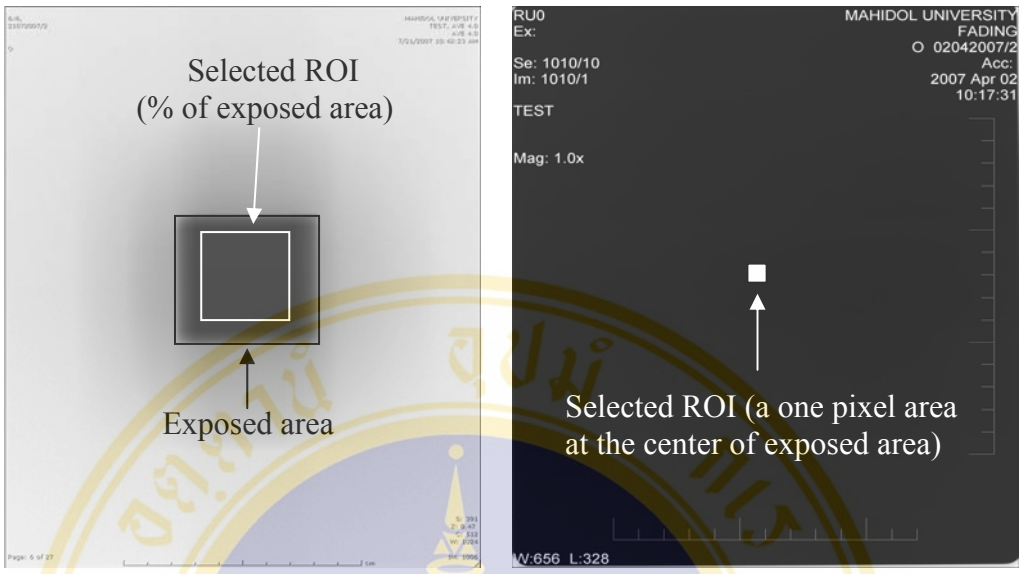

(a) (b)

Figure 4.7 How to select ROI on a DICOM image. (a) ROI is selected as a percentage of exposed area and (b) ROI is selected as a PSP plate pixel size at the center of exposed area.

4.2.2 Factor affecting on the determination of digital pixel values

A. Effect of PSP plate fading

It was found that after the PSP plate was irradiated the stimulated signal would be fading with time before reading (9). The time interval from irradiated to readout signals was defined as fading time. This phenomenon is therefore direct affect on digital pixel values. The fading effect of the 20x25 cm Fuji PSP plate was investigated. The PSP plate was removed from its cassette and placed on a foam box at 25 cm above the floor as shown in figure 4.8. A lead sheet was placed on floor underneath the PSP to minimize backscattering. The Focal-Detector Distance (FDD) was set at 180 cm. The x-ray tube collimator was adjusted with a 3 cm margin outside of the PSP plate. The PSP plate was exposed with tube voltage at 80 kVp and 10 mAs. Before exposed, the removing of residue signals from natural radiation was performed using the primary erasure mode of FCR reader. After irradiated, the signal of each PSP plate was read in terms of pixel value with the fixed mode of FCR reader using S=200 and L=4 at each 1 min interval up to 10 min. The fading effect was determined in terms of the fading rate which was defined as the ratio of the digital pixel value

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measured at a fading time to the pixel value measured at 1 min fading time. The fading effects were examined in the conditions of the room light turned off, light turned on, and light turned on with the PSP kept into cassette immediately after irradiation.

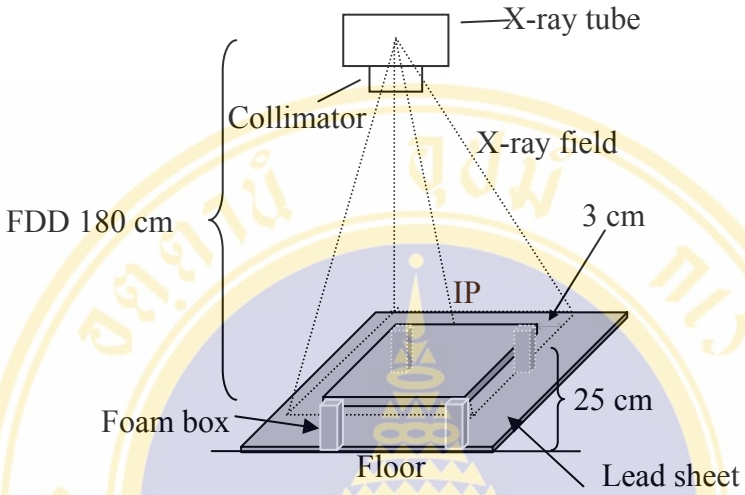

Figure 4.8 The experimental set up for measuring of fading effects.

B. Cassette Effect

It is know that the amount of photostimulable luminescence (PSL) from the PSP plate is direct proportion to the radiation exposure on the PSP plate itself. Therefore, the using of PSP plate with or without cassette should be as a result of different reading of the digital pixel value. The effect of cassette on the pixel value reading was determined by exposing the PSP plate of 20x25 cm with and without cassette for tube voltage of 80 kVp at various mAs of 10-64 mAs. The measurement set up was the same as shown in figure 4.8. The pixel values were determined according to the method described in section 4.2.1.

C. Effect of the positioning exposed area on the coordinate (x, y)

Since the pixel value was calculated from a selected ROI of exposed area and the value of ROI area was inserted into MATLAB program in terms of the coordinate (x, y). The effect of the positioning of the coordinate (x, y) was also investigated. The PSP plate size 20x25 cm without cassette was exposed with 6x6 cm of 80 kVp x-ray beam. The selected ROI from one pixel size area at center to full expose are selected in terms of coordinate (x, y). It was found that the coordinate (x, y) was selected with

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±5 pixel due to the percentage difference was less then 1%.

4.2.3 The calculation of exposure from pixel values

According to Fuji PSP plate with EDR reader, the radiation exposure (E, in mR) relates to the digital pixel value (PV) as shown in the Eq. (4.1) which is the same as Eq. (3.2).

$$E = \frac{10^{L/1024(PV-511)}}{S \cdot k} \tag{4.1}$$

Where S is the S number or sensitivity in range from 4 to 20000, and the L is number or latitude in range from 0.5 to 4. The S and L values adjusted according to the mode selected (auto, semi, or fixed) will provide an optimum contrast and density for clinical images. The k is the constant value.

Before using Eq. (4.1), the k value was determined by the following equation.

$$k = \frac{10^{L/1024(PV-511)}}{S \cdot E} \tag{4.2}$$

where E in this equation means the correct exposure which would measure with ionization chamber.

4.2.4 Dosimetric measurements

For all dosimetric measurements using PSP plate, the pixel value from the PSP plate irradiated was converted to exposure using Eq. (4.1) with the k-value determined from Eq. (4.2). The PSP dosimetric measurements were compared with ionization measurements for all investigated. The dosimetric measurements are studied as the following.

4.2.4.1 Exposure measurements with and without cassette

The measurement set up for the PSP plate was the same as figure 4.8. The ionization chamber was placed in air at the same position as the PSP as shown in

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figure 4.9. This method followed cassette effect in section B of 4.2.2. Each dosimeter was irradiated for three times and the exposures were calculated and averaged.

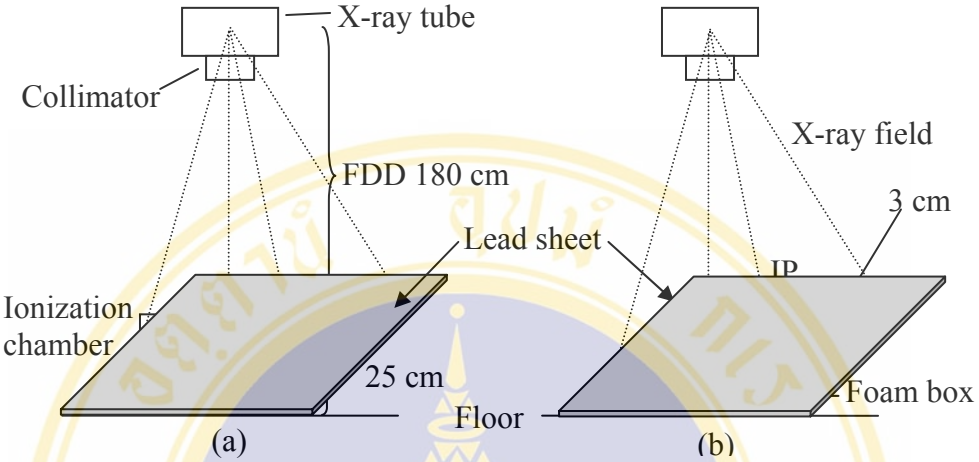

Figure 4.9 The experimental set up for dosimeteric measurements when (a) is the measurement with ionization chamber and (b) the PSP plate measurement.

4.2.4.2 Exposure measurements from various selected ROI area and various exposed area

The effect of selected ROI area and/or exposed area on the calculated exposure from the 20x25 cm PSP exposed with x-ray tube voltage from 40 to 120 kVp, 10 mAs at 100 cm FDD and different field size of 6x6 cm to 18x18 cm were investigated. The experimental set up was set as shown in figure 4.10. The semi-auto mode was selected for PSP plate readout processing using L=4.

At an exposed area, the ROI areas for calculation of average pixel values were selected as shown in figure 4.11. The ROI area was selected at the center as a percentage of exposed area.

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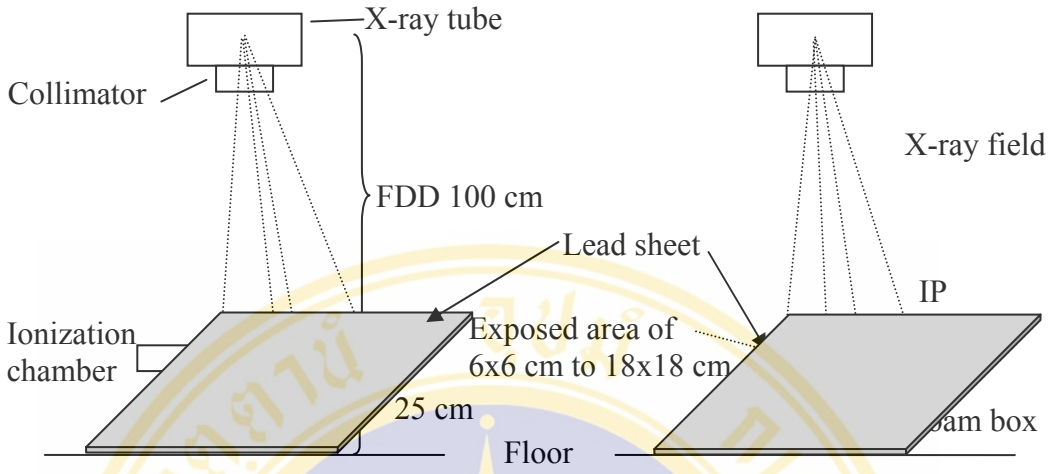

Figure 4.10 The experimental set up for exposure measurement at different exposed area.

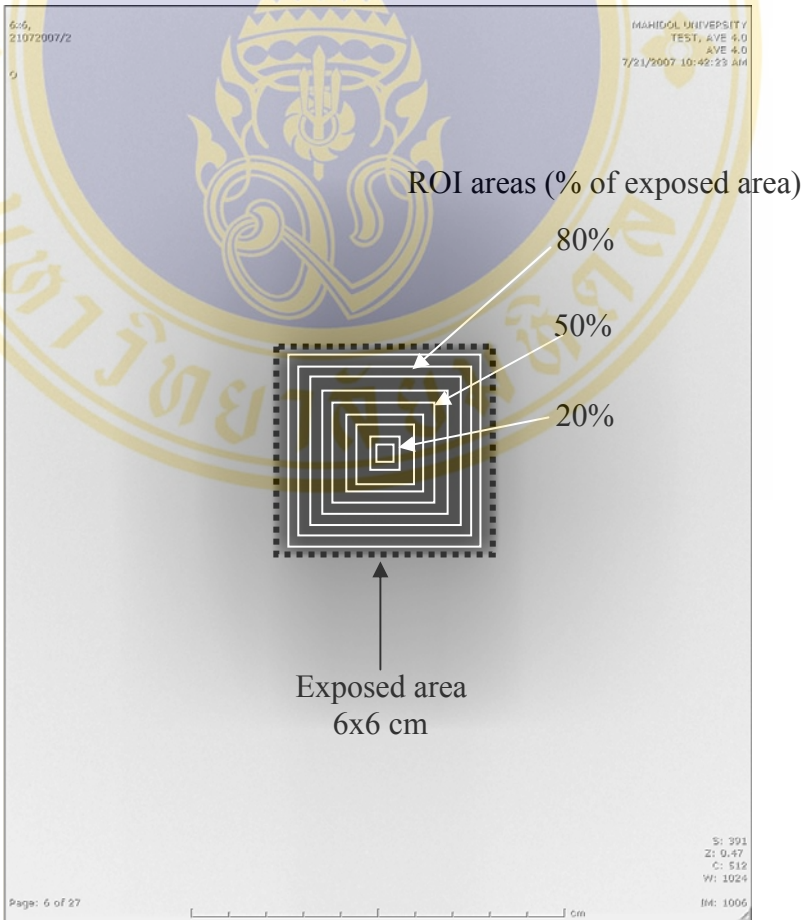

Figure 4.11 The different selected ROI areas as a percentage of exposed area.

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4.2.4.3 Exposure measurement with different PSP pixel sizes

For a larger PSP plate size, it is normally constructed of a larger PSP pixel size as can be seen also in table 4.2 for the Fuji PSP plate. It is interested, therefore, to investigate the effect of different PSP pixel size on exposure measurements. The PSP plate sizes of 20x25, 35x35 and 35x43 cm having PSP pixel sizes of 100, 150, and 200 μm, respectively were exposed with tube voltage of 80 kVp in the same condition and set up as described in the section A of 4.2.2. The difference of calculated exposures from different PSP pixel sizes were compared with the exposures measured with ionization chamber at the same conditions.

4.2.4.4 Energy dependence on exposure determination from PSP plate

It was found that the x-ray beam energy significant affects on pixel value determination (9). This effect was investigated for tube voltage from 40 to 120 kVp in terms of correction factor (CF). The correction factor is defined as the ratio of measured exposure from ionization chamber measurement to calculated exposure from PSP plate measurement.

4.2.4.5 Utilize of PSP plate for measurements of x-ray exposure

A. Measurements with PSP plate exposed from various kVp

The x-ray exposure at 100 cm FDD of tube voltage from 40 to 120 kVp at 6x6 cm^2 field size was measured with the 20x25 cm PSP plate exposed with 10 mAs and then compared with ionization chamber measurement at the same conditions. A free-in-air measurement was applied for each exposure as shown in figure 4.12. Each measurement was repeated for 3 times and the output is then averaged in terms of mR/mAs. For PSP plate measurement, the signals were read at ROI of 80% exposed area and L = 4. The average pixel values were converted to exposure by using Eq. (4.1). The average mR/mAs at various kVp were plotted and compared with ionization chamber measurement.

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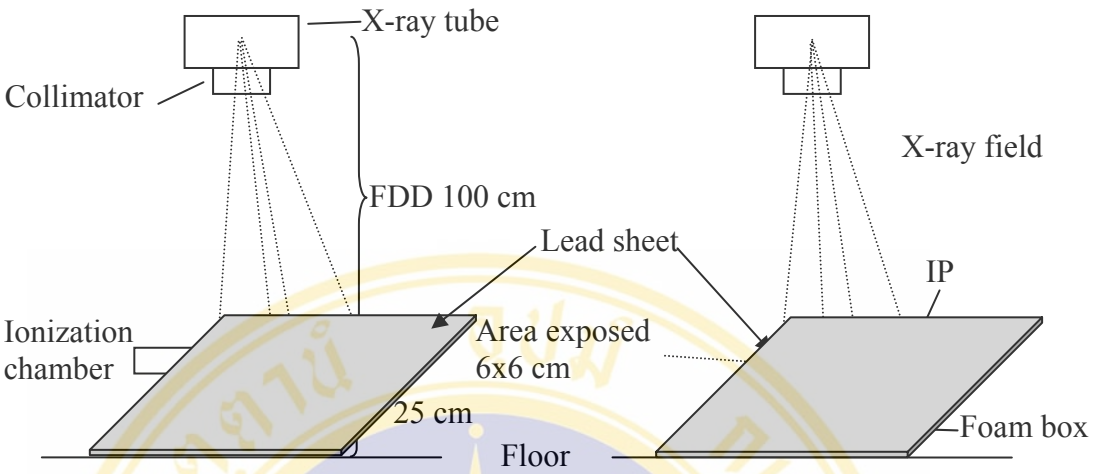

Figure 4.12 X-ray output measurements at 100 cm FDD using the PSP plate dosimeter and the ionization chamber.

B. Measurements with PSP plate exposed at various mAs

The x-ray output of tube voltage from 40 to 120 kVp at 6 x 6 cm field size and various mA of 25, 100, 200, 250 and 500 mA as total 5 mAs were measured with the PSP plate and ionization chamber. For the PSP plate measurements, the signals were read at ROI of 80% exposed area and L=4. Each measurement was repeated 3 times and the results were averaged. The average exposures from PSP plate measurements were calculated and compared with ionization measurements in terms of mR/mAs.

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CHAPTER V
RESULTS

5.1 Factors affecting on the reading of digital pixel values

5.1.1 Effect of PSP plate fading

Figure 5.1 show the variation of fading rate with fading time which was normalized to 1 min after irradiation for conditions of the room light turned off, turned on and turned on with PSP plate kept into cassette immediately after irradiation. In general, the fading rates were decreased with increasing fading time. The fading rates were rapidly decreased to 8% in 10 min when the room light was turned on and decreased to 76% in 10 min when the light was turned off. With keeping the PSP plate in cassette immediately after irradiation and turned on the room light, the fading rates showed a small decrease of less than 3% in 10 min.

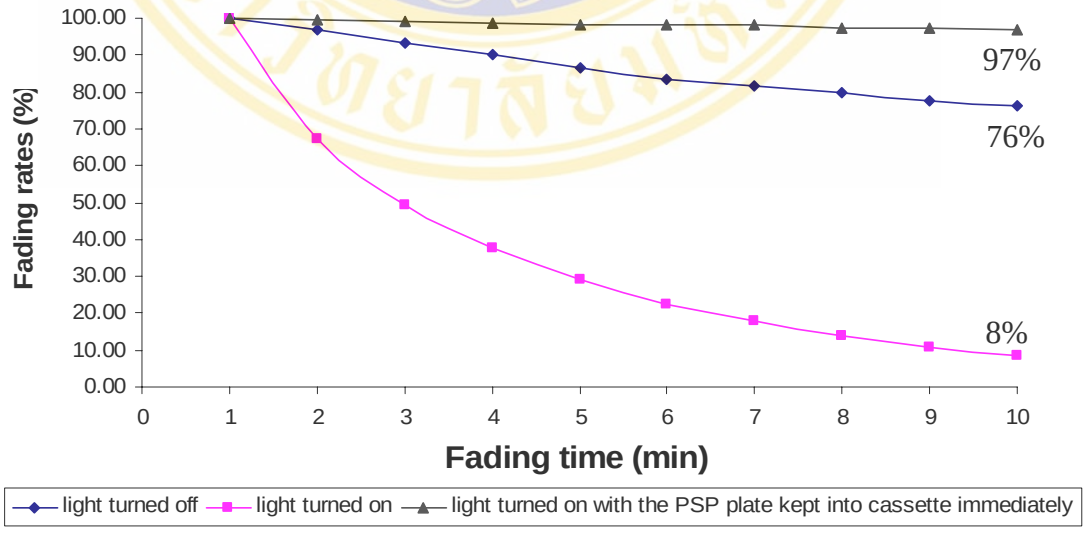

Figure 5.1 A comparison of the fading rate of the pixel values when the room light was turned off, turned on, and turned on with PSP plate kept into cassette immediately after irradiation.

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5.1.2 Cassette Effect

The calculated on digital pixel values from the exposed 20x25 cm PSP plate with and without cassette with 80 kVp x-ray beam at various mAs of 10-64 mAs as ROI area selected from one pixel area to 60% of exposed area are shown in table 5.1 with the standard deviation. The pixel value of PSP plate exposed without cassette as ROI area selected of one pixel area, 60% of exposed area and all ROI area selected shows approximately 1.34%, 1.24% and 1.29% lower than with cassette, respectively.

Table 5.1 A comparison of pixel values calculated of the ROI selected from one pixel area to 60% of exposed area of 20x25 cm PSP plate with and without cassettes exposed with 80 kVp x-ray beam at various mAs.

	With cassette		Without cassette	
mAs	One pixel area	60% of exposed area	One pixel area	60% of exposed area
10	830	821.20	816	808.20
12.6	859	849.78	844	836.63
16	889	879.02	874	866.32
20	916	905.77	902	893.18
25	943	932.65	928	920.08
32	972	962.25	956	948.75
40	999	988.91	985	975.84
50	1023	1014.90	1011	1001.87
64	1023	1020.20	1023	1020.20
Mean	939.33	930.52	926.70	919.01
SD	70.82	71.87	73.29	73.93
All mean ± SD	934.93 ± 69.36		922.86 ± 71.53	

The average pixel values of the PSP exposed without cassette at 40-120 kVp x-ray beam were investigated further at selected ROI area up to 100% of exposed area 6x6 cm. The results are shown in figure 5.2 and the data are collected in table B.1 of appendix B. The pixel values are constant at selected area less than 60% and then decease rapidly as increasing selected area.

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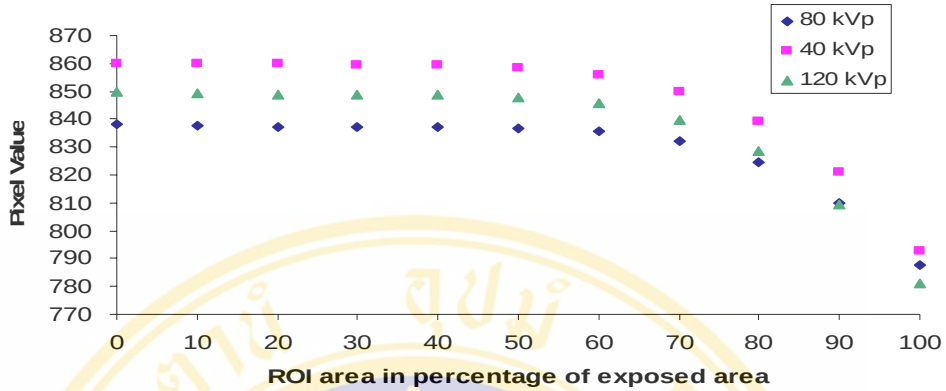

Figure 5.2 The pixel values of selected ROI area in percentage of exposed area as various kVp x-ray beams.

5.2 The calculation of exposure from pixel values

The k-value was calculated from Eq. (4.2) by measuring average PV from exposed of 20x25, 35x35 and 35x43 cm from selected ROI at center to 60% of exposed area. The average calculated k-values for each PSP plate are showed in table 5.2 (see also in table B.2 of appendix B) with their standard deviations. It can be seen that the overall average the k value is 0.0046, therefore, the k value of 0.005 as recommended by Liu (14) were used for all exposure calculations in this study.

Table 5.2 The calibrated k values of PSP plate sizes in selected pixel values.

	Plate size					
	20x25 cm		35x35 cm		35x43 cm	
mAs	One pixel area	60% of exposed area	One pixel area	60% of exposed area	One pixel area	60% of exposed area
10	0.00522	0.00481	0.00447	0.00418	0.00460	0.00431
12.6	0.00448	0.00422	0.00469	0.00440	0.00469	0.00434
16	0.00437	0.00410	0.00473	0.00446	0.00457	0.00426
20	0.00448	0.00422	0.00472	0.00445	0.00456	0.00422
25	0.00470	0.00438	0.00471	0.00440	0.00450	0.00421
32	0.00541	0.00496	0.00490	0.00459	0.00464	0.00429
40	0.00538	0.00492	0.00496	0.00462	0.00479	0.00181
50	0.00556	0.00507	0.00495	0.00464	0.00486	0.00450
64	0.00486	0.00472	0.00485	0.00466	0.00486	0.00454
Mean	0.00494	0.00460	0.00478	0.00449	0.00467	0.00405
SD	0.00046	0.00037	0.00016	0.00016	0.00013	0.00085
All mean ± SD is 0.0046 ± 0.0005						

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5.3 Exposure measurements with and without cassette

From the results of calculated average pixel values of with and without cassette at each ROI selected in table 5.1, the exposures of all pixel values were calculated from Eq. (4.1) and compared. The results are shown in table 5.3 with the standard deviations. The calculated exposure of PSP plate exposed without cassette as ROI area selected of one pixel area, 60% of exposed area and all ROI area selected shows approximately 9.43%, 8.73% and 9.10% lower than with cassette, respectively.

The exposures calculated from PSP plate exposed with and without cassette were also compared with the exposures measured with ionization chamber at selected ROI area from one pixel size area to 60% of exposed area as shown in table 5.4. The exposures calculated from PSP plate exposed without cassette nearly measured with ionization chamber. The average exposures of PSP plate with and without cassette are 2.39% and 14.35% higher than the measured with ionization chamber in all factors investigated, respectively. Therefore, for the further exposure measured with PSP plate, the PSP plate exposed without cassette would be used.

Table 5.3 A comparison of exposures calculated from the ROI selected from one pixel area to 60% of exposed area of 20x25 cm PSP plate with and without cassettes exposed with 80 kVp x-ray beam at various mAs.

	With cassette		Without cassette	
mAs	One pixel area	60% of exposed area	One pixel area	60% of exposed area
10	17.62	16.28	15.59	14.49
12.6	22.88	21.06	20.05	18.71
16	29.96	27.39	26.26	24.43
20	38.20	34.84	33.68	31.11
25	48.70	44.37	42.55	39.63
32	63.21	57.90	54.90	51.28
40	80.58	73.59	71.05	65.43
50	100.00	92.97	89.77	82.69
64	100.00	97.51	100.00	97.51
Mean	55.68	51.77	50.43	47.25
SD	31.91	30.50	30.65	29.28
All mean ± SD	53.73 ± 31.35		48.84 ± 29.12	

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Table 5.4 The percentage differences of exposures calculated from 20x25 cm PSP plate exposed with and without cassette with ROI selected from one pixel area to 60% of exposed area were compared with the exposures measured with ionization chamber (IC).

	With cassette		Without cassette	
IC	One pixel area	60% of exposed area	One pixel area	60% of exposed area
14.87	18.49	9.47	4.79	-2.61
19.19	19.23	9.74	4.49	-2.50
24.82	20.70	10.34	5.78	-1.57
31.45	21.47	10.79	7.09	-1.07
39.64	22.85	11.93	7.34	-0.03
51.23	23.39	13.03	7.17	0.10
64.42	25.10	14.25	10.30	1.57
81.04	23.39	14.72	10.77	2.03
104.30	-4.12	-6.51	-4.12	-6.51
mean	18.94	9.75	5.96	-1.18
SD	8.91	6.39	4.36	2.58
All mean ± SD	14.35 ± 8.88		2.39 ± 5.05	

5.4 Exposure calculated from ROI area selected with various exposed area of 40 to 120 kVp x-ray beam

The exposures of 80 kVp x-ray beam calculated from the average pixel values of different selected ROI up to 80% of exposed area 6x6 cm to 18x18 cm were determined and compared with the exposures measurement with ionization chamber at the same beam and position. The comparison is shown in figure 5.3 and the data are colleted in table B.3 of appendix B in terms of percentage differences.

In general, it can be said that the calculated exposures depend to some extend on the selected ROI area with a slightly decreasing with increased ROI area up to 60% of exposed area for all the exposed area investigated. The exposures measured with PSP plate are higher than these measured with ionization chamber and the percentage of higher increases with the exposed area decreases. The calculated exposures from PSP plate show a better agreement when a larger ROI area is selected and/or an exposed area increased. The selected ROI area of 80% shows the best agreement of less than ±2% with ionization chamber measurement for all exposed area investigated.

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It is noted that the results of ROI area lager than 80% are ignored because the average pixel values of these area were found to be much lower than expected due to the penumbra regions were taken into account.

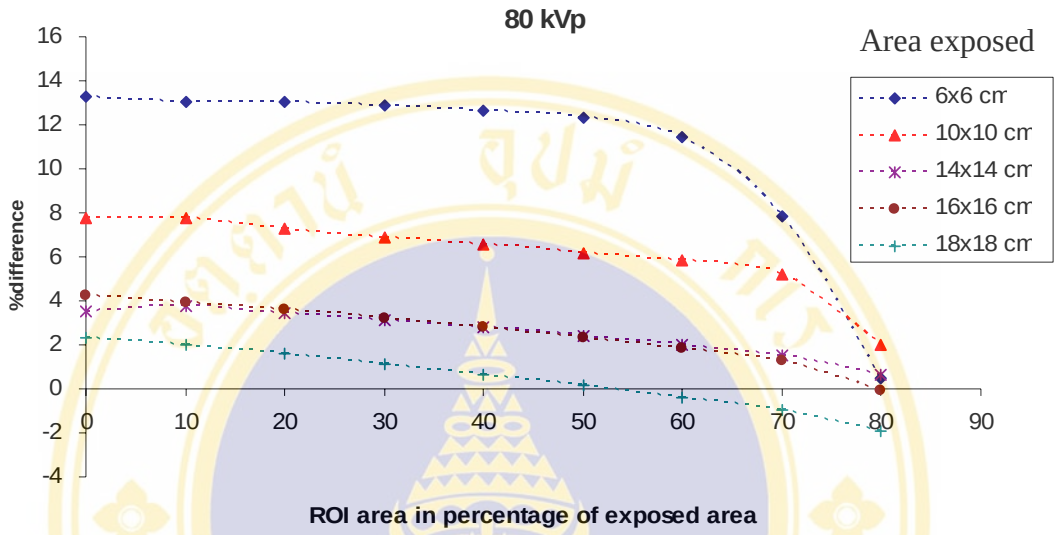

Figure 5.3 The comparison of exposures calculated from the various selected ROI area of exposed area from 6x6 cm to 18x18 cm of 80 kVp x-ray beam with the exposures measured with ionization chamber at the same setup in terms of percentage differences.

The percentage difference of exposures calculated from PSP plate exposed without cassette at ROI area 80% of various exposed area from 40 to 120 kVp x-ray beam are shown in figure 5.4 and the data are collected in table B.4 of appendix B. The exposure measured from PSP plate shows the lower exposure at low kVp but slightly higher at high kVp for all exposed area. As a result, the exposure measured from IP would depend on x-ray energy.

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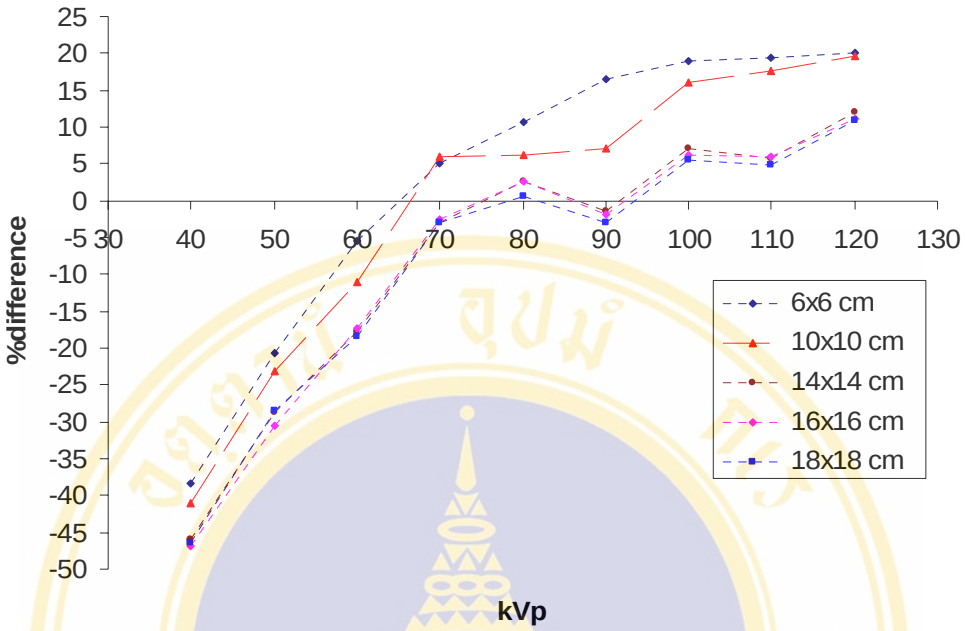

Figure 5.4 The variation of exposure calculated from PSP plate exposed without cassette at ROI area 80% of 6x6 cm to 18x18 cm exposed area from 40 to 120 kVp x-ray beam.

5.5 Exposure measured from the different exposed PSP plate sizes

The calculated exposures from PSP plate sizes of 20x25, 35x35 and 35x43 cm exposed without cassette with 80 kVp x-ray beam at ROI selected from one pixel area to full PSP area were compared with the exposures measured with ionization chamber at the same conditions in terms of percentage differences. The results are shown in table 5.5 (see also in table B.5 of appendix B). As the PSP plate sizes (PSP pixel size) increased, the percentage differences trend to be decreased from -4.6% to -9.8%. However, the larger of standard deviation can be noted for the smaller PSP plate size. The negative differences indicate the lower exposures calculated from PSP plate than from ionization chamber measurement due to the large exposed area used. It can be said that a smaller PSP plate size would give a more proper result of calculated exposure.

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Table 5.5 The percentage differences of calculated exposures from PSP plate sizes of 20x25, 35x35 and 35x43 cm without cassette exposed with 80 kVp x-ray beam at various mAs of 10-64 mAs at ROI selected from one pixel area to full PSP area compared with the exposure measured with ionization chamber.

	Plate size					
	20x25 cm		35x35 cm		35x43 cm	
mAs	One pixel area	Full PSP area	One pixel area	Full PSP area	One pixel area	Full PSP area
10	4.38	-3.71	-10.42	-16.48	-7.97	-13.81
12.6	-10.40	-15.61	-6.27	-11.94	-6.27	-13.26
16	-12.67	-18.01	-5.31	-10.86	-8.65	-14.76
20	-10.33	-15.51	-5.36	-11.00	-8.70	-15.51
25	-5.95	-12.45	-5.95	-11.94	-10.09	-15.77
32	8.19	-0.75	-2.00	-8.12	-7.15	-14.27
40	7.64	-1.69	-0.73	-7.65	-4.24	-11.15
50	11.13	1.31	-1.13	-7.26	-2.89	-10.02
64	-2.88	-5.55	-2.88	-6.82	-2.88	-9.30
Mean	-1.21	-8.00	-4.45	-10.23	-6.54	-13.09
SD	9.18	7.40	3.08	3.11	2.65	2.38
All mean ± SD	-4.60 ± 8.81		-7.34 ± 4.23		-9.82 ± 4.16	

5.6 Energy dependence on pixel value determination

The x-ray energy dependence of average pixel values as a result of exposure calculated was investigated. The energy dependence was defined in terms of correction factor as the ratio of measured exposure from ionization chamber measurement to calculated exposure from IP measurement. The calculated exposures from 20x25 cm PSP plate exposed without cassette at ROI area at center up to 80% of various exposed areas of 6x6 cm to 18x18 cm from 40 to 120 kVp and 10 mAs were used to determine the correction factor.

The correction factors for energy dependence of 20x25 cm PSP plate on x-ray beam energies of 40 to 120 kVp are shown in figure 5.5 and the data are collected in table B.6 of appendix B. Each value of correction at particular x-ray energy is the average from the data of various exposed areas. At 70 kVp x-ray or higher, it would say that the IP as a dosimeter, the measured exposure dose not depend on the x-ray beam energy. However, higher energy dependence can be seen at the lower x-ray beam energy.

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The correction factor shown in figure 5.5 was fitted with a polynomial function:

$$y = -4.99 \times 10^{-6} x^3 + 1.43 \times 10^{-3} x^2 - 0.136x + 5.23 \quad (5.1)$$

Table 5.6 shows the correction factors at various kVp calculated from Eq. (5.1).

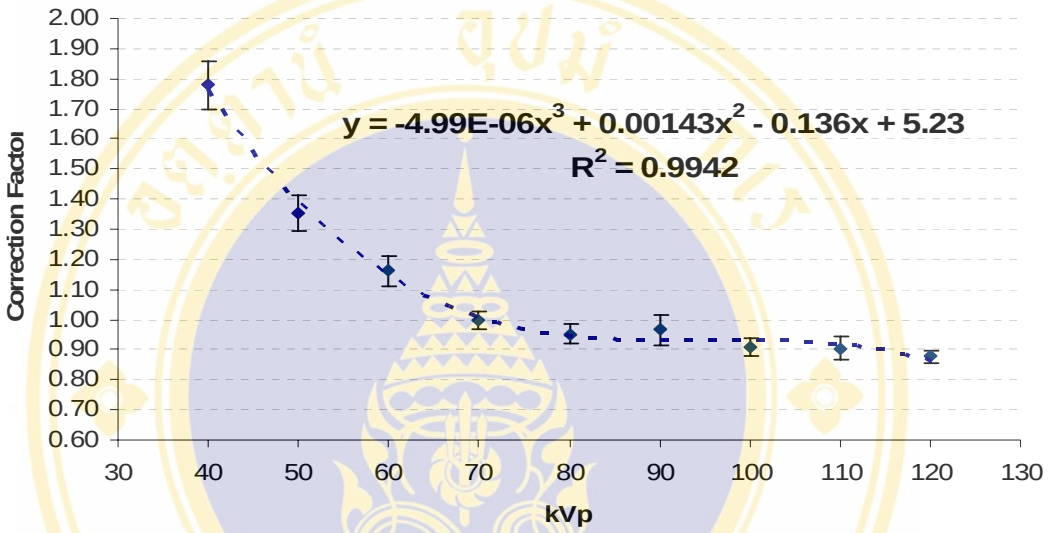

Figure 5.5 The correction factor for energy dependence of 20x25 cm PSP plate exposed without cassette using as a detector for measurement of x-ray exposure. The correction factor is fitted with a polynomial function as shown with $R^2 > 0.99$.

Table 5.6 The correction factor calculated from Eq. (5.1) for energy dependence of 20x25 cm PSP plate exposed without cassette.

kVp	Correction factor (CF)
40	1.76
50	1.38
60	1.14
70	1.01
80	0.95
90	0.94
100	0.94
110	0.93
120	0.88

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5.7 X-ray exposures at various kVp measured with 20x25 cm PSP plate

The x-ray exposure at 100 cm FDD of 40 to 120 kVp beam at 6x6 cm field size using the PSP plate without cassette were compared with ionization chamber measurement at the same conditions. The pixel values of PSP plate measurement were read at ROI of 80% of exposed area. The exposure in terms of mR/mAs at various kVp is shown in table 5.7 and figure 5.6.

The correction factor for x-ray energy dependence on PSP plate as described in table 5.6 was applied for all kVp investigated. The exposures from both measuring methods show an agreement within ±4% which is the accuracy of ionization chamber (IC) as can be seen in the last column of table 5.7 for all kVps.

Table 5.7 X-ray exposures measured with 20x25 cm PSP plate compared with ionization chamber measurements.

	Exposure (mR)		mR/mAs			
kVp	IC	PSP	IC	PSP	PSP corrected	%difference
40	3.43	2.10	0.69	0.42	0.67	-2.06
50	6.85	5.54	1.37	1.11	1.39	1.62
60	10.30	9.91	2.06	1.98	2.06	-0.22
70	14.38	15.25	2.88	3.05	2.79	-3.00
80	18.70	21.23	3.74	4.25	3.66	-2.17
90	23.55	27.78	4.71	5.56	4.73	0.41
100	28.93	34.75	5.79	6.95	5.95	2.77
110	35.11	42.50	7.02	8.50	7.20	2.60
120	41.56	50.42	8.31	10.08	8.07	-2.93

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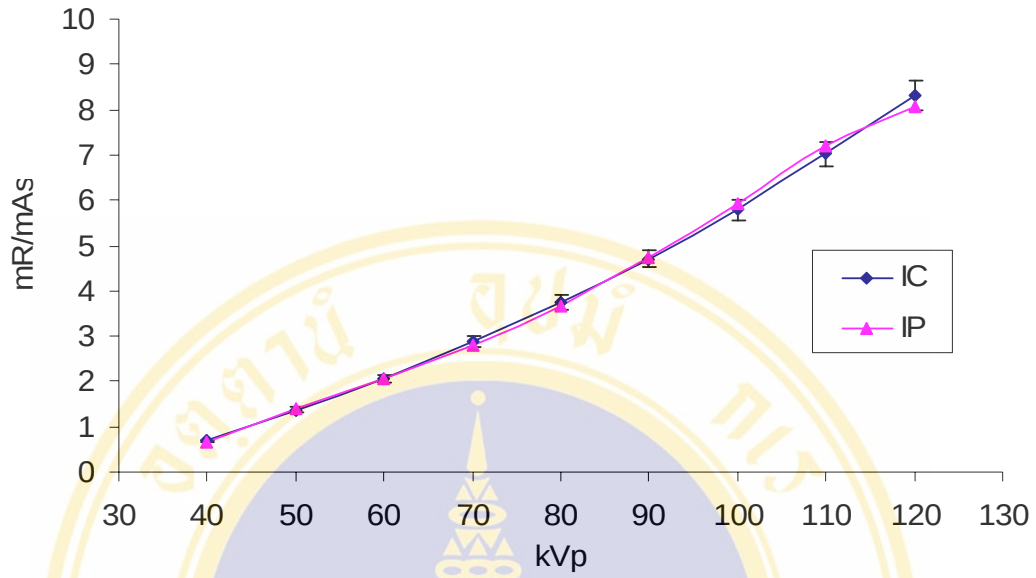

Figure 5.6 The comparison of x-ray exposures at various kVp measured with 20x25 cm PSP plate and ionization chamber. The error bars indicate the accuracy of ionization chamber measurement which is ±4%.

5.8 X-ray exposures at various mAs measured with 20x25 cm PSP plate

The x-ray exposures measured with the same PSP plate and conditions as described in section 5.7 were determined for various mA setting of 25 to 500 mA of 40-120 kVp beams. The correction factors x-ray energy dependence on IP were applied. The results were compared with ionization chamber measurements as shown in figure 5.7 and the data are collected in table B.7 of appendix B. The agreement within the accuracy of ionization measurement (±4%) of exposure measured with both methods can be seen for all mA and kVp investigated.

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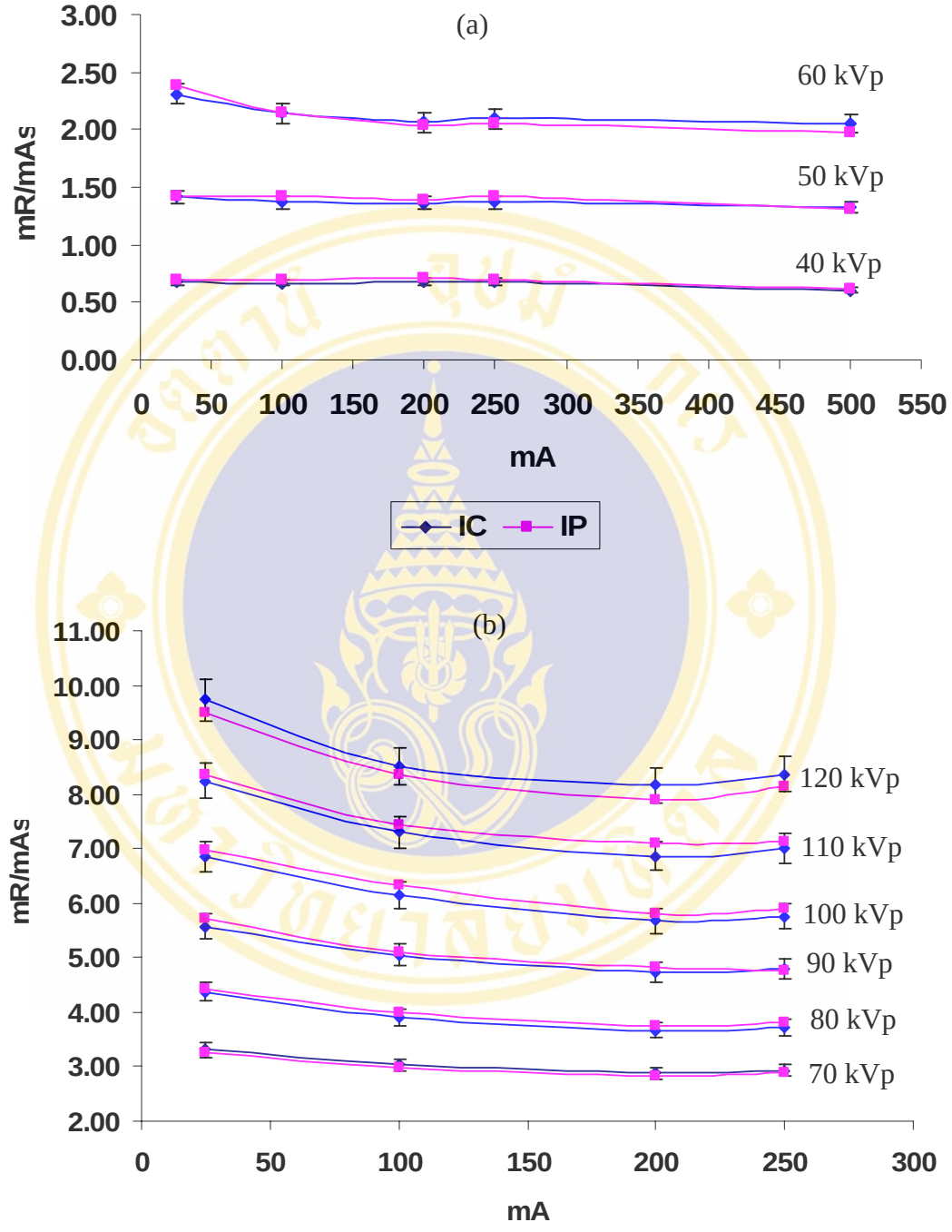

Figure 5.7 The comparison of exposures at various mA measured with 20x25 cm PSP plate and ionization chamber (a) at 40 to 60 kVp and (b) at 70 to 120 kVp. The error bars indicate the accuracy of ionization chamber measurements which is ±4%.

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CHAPTER VI
DISCUSSION

6.1 Effect of PSP plate fading

The fading rate of Fuji PSP plate exposed without cassette was found to be less than 3% in 10 min when it was kept immediately into its cassette after exposed even though the room light was turned on. In this study the length of time to carry the exposed PSP plate to readout is less than 1 minute, the fading effect therefore can be ignored. Ariga et al, 2007 (13) found that the fading of Fuji PSP plate exposed with cassette for 4 min after irradiation was less than 1.9% when it was normalized to 2 min compared with my result of 1.6% normalized to 1 min.

6.2 The calculation of exposure from an exposed PSP plate

The exposure and pixel value relationships are $E = \frac{10^{L/1024(PV-511)}}{S \cdot k}$. In this equation, beside of pixel value it can be seen that the exposure is also dependable on S, L and k values. The S and L can be varied depending on the EDR mode selected. For the k value, it was calculated using equation $k = \frac{10^{L/1024(PV-511)}}{S \cdot E}$ and was found to be 0.0046±0.0005 which is agreed very well with report of Liu et al, 2005 (14).

6.3 Cassette effect

The average pixel value reading from IP exposed without cassette was found to be approximately 1% lower than exposed with cassette due to a slight attenuation effect of the x-ray beam by cassette (14). As a result of about 9% lower exposure calculated from PSP plate exposed without cassette would be expected. The exposures calculated from PSP plate exposed without cassette compared with the exposure measured with ionization chamber was found to be better agreement than with

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cassette. An average agreement within 2.4 ± 5.0 % higher for without cassette was found in compared with 14.4 ± 8.9 % for with cassette.

6.4 The dependence of calculated exposures from the exposed PSP plate

6.4.1 The ROI area selected for PV determination

For 20x25 cm PSP plate exposed with 80 kVp beams at the 6x6 cm^2 to 18x18 cm^2, in general the calculated exposures were found decreasing with increasing selected ROI area for all exposed area investigated. If the smallest ROI selected (one pixel size area) was used to calculate exposure the resultant exposure would be always higher than large ROI selected. The exposure was better agreeable with the exposures measured from ionization chamber when a larger ROI area was selected. The ROI of 80% of exposed area was found to give the best agreement. With the larger exposed area the calculated exposures gave the better agreement with the exposure measured from ionization chamber. The exposed area of 14x14 cm^2 or lager was found to give a good agreement.

6.4.2 The different PSP plate sizes

For Fuji PSP plate, the lager PSP sizes from 100 μm to 200 μm were exposed with different exposed areas of various x-ray tube voltages. The percentage difference of average calculated exposure and exposure measured with ionization chamber was found to be decreased significantly from -4.6±8.8 % to -12.7±13.4 %. It would suggest that a smaller PSP size (smaller PSP plate size) would give a more proper result of calculated exposure.

6.4.3 The x-ray beam energies

The exposure calculated from an exposed Fuji PSP plate was found to be x-ray beam energy dependence. This effect was more pronounced at the lower tube voltage lower than 70 kVp. Tucker et al, 1997 (9) reported the high variations of measured pixel value occur at low tube voltage investigated at 60 kVp. The correction factors (CF) for energy dependence on tube voltage of 40 to 120 kVp were determined and

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found to be fitted with an equation of CF = $-4.99 \times 10^{-6} x^3 + 1.43 \times 10^{-3} x^2 - 0.136x + 5.23$, where x is the x-ray energy in kVp.

For a 20x25 cm PSP plate exposed with a 6x6 cm^2 area of various tube voltage (40 to 120 kVp), if the exposures would agreeable within ±4% with the exposure measured with ionization chamber for all kVp investigated.

6.5 The x-ray exposures at various kVp and mA setting measured with 20x25 cm PSP plate.

The x-ray exposure at 100 cm FDD of 40 to 120 kVp beam and 25 to 500 mA setting at 6x6 cm^2 field size using PSP plate without cassette were compared with measured with ionization chamber at the same conditions in terms of mR/mAs. If the correction factors were applied the agreement within ±4% was found for all investigated. The dosimetry using the 20x25 cm Fuji PSP plate without cassette and the equation can estimate the exposure dose in a range from 25.8×10^{-4} to 25.8 $\mu C\ kg^{-1}$.Ariga et al, 2007 (13) found that the PSP plate exposed with cassette within ±5% was found for all exposure dose in a range from 9.0×10^{-2} to 5.0 $\mu C\ kg^{-1}$.

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CHAPTER VII
CONCLUSION

A method for dosimetry using the PSP plate of computed radiography system as a detector was developed. The exposures calculated using the PSP plate were agreed within ±4% with ionization chamber measurement.

The PSP plate without cassette was used to exposed in an exposed area of x-ray beam and put it into cassette immediately after irradiation. Then, the average pixel value was determined from ROI area at 80% of exposed area in order to convert to calculated exposures. Finally, the exposures equation was applied with the correction factor for energy dependence of that tube voltage setting.

Factors affecting of using PSP plate were realized. The exposed PSP plate without cassette must be put immediately back to its cassette for carrying to read in order to avoid the PSL fading. The exposure equation should be somewhat different depending on the type and brand of the PSP plate and should be verified. The PSP plate exposed without cassette should be employed for dosimetric measurement. The calculated exposures depend on the ROI selected for PV determination. An agreement within a few percent between the exposure calculated from exposed PSP plate and measured with ionization chamber can be expected when the large ROI and/ or the large exposed area are selected. The smaller PSP size (smaller PSP pixel size) would give a more proper result of calculated exposure. The response of exposed PSP in PSP plate depends on tube voltage of x-ray machine. Any attempt for using the PSP plate as an exposure measurement especially at x-ray tube voltage lower than 70 kVp, the correction factor for x-ray beam energy dependence should be found out and applied.

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22. http://www.radcal.com/9095.html

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APPENDIX

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APPENDIX A
MATLAB SOURCE CODE
FOR DETERMINATION OF PIXEL VALUE

In this study, a function M-file of MATLAB was used. The function M-file accepts input arguments and return output arguments. They operate on variable within their own workspace. The function M-file consists of function header, comment line, help text, function body, and comments. The general pattern of the function header is:

function [a,b,c] = function_name (x,y,z)

where [a,b,c] is the output variable list in square bracket.
function_name is the name of the function (function_name.m).
(x,y,z) is the input variable list in parentheses.
The name of the M-file and the function should be the same.

The comment line and the help text provide summary information about the function M-file. The function body contains all the MATLAB code that performs computations and assigns values to output arguments. Finally, the comments provide information to help user understanding.

In this study, the pixel values were determined using the values of exposed area, ROI area as a percentage of exposed area, and the position of the center pixel of ROI area on the coordinate (x,y). Each PSP plate size shows matrix size and coordinate (x,y) at center as shown in table A.1.

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Table A.1 The coordinate (x,y) at center of each PSP plate size.

Size (cm x cm)	Matrix size (pixel x pixel)	coordinate at center (row,column)
20 x 25	2000 x 2510	(1255,1000)
35 x 35	1760 x 1760	(880, 880)
35 x 43	2140 x 1760	(880, 1070)

For detail of function the looping statement namely *for* loop was used. The *for* loop allows repetition of a group of MATLAB commands. A general form of a *for* loop is

for n = a : s : b

This pattern means the value repeated as n counts from a to b as a step of s.

The header of function M-file was modified from general pattern for determination of pixel value.

function[a]=area_FS(x,y,FS,q,r,s);

where [a] is a pixel value averaged on ROI area selected.

x,y are the coordinate at center.

FS is the area exposed.

(q,r,s) is ROI area selected as a percentage of area exposed from initial ROI area selected to final ROI area selected as step ROI increments.

The source codes for determination the pixel value are shown in figure A.1.

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```
function[a]=area_FS(x,y,FS,q,r,s);                    Fuction header
%this function is used to determine pixel value
%with ROI area selected as percentage of area exposed   Comment line
%input :( x, y) =coordinate at center of ROI,
%FS=area exposed (no. of pixel),
%(q,r,s)= ROI selected                                  Help text
%output: ROI as a percentage of area exposed
%saves as area_FS.m
x=input('x=');          %coordinate x (row) at center of ROI
y=input('y=');          %coordinate y (column) at center of ROI
FS=input('Area exposed='); %area exposed in pixel dimensions
                                %depends on the IP pixel sizes   Comments
q=input('Initial ROI selected as % of area exposed =');
r=input('Final ROI selected as % of area exposed =');
s=input('ROI increments as % of area exposed =');
i=dicomread ('6x6_0.dcm');   %function for reading of DICOM image file
i=double (i);
for q=q:s:r                                                Function body
   A=x-round(((((FS^2)*(q/100))^0.5)*0.5));
   B=x+round(((((FS^2)*(q/100))^0.5)*0.5));
   C=y-round(((((FS^2)*(q/100))^0.5)*0.5));
   D=y+round(((((FS^2)*(q/100))^0.5)*0.5));
   matrix=i(A:B,C:D);
   a=mean(mean (matrix));
   disp('a=');disp(a);
end
```

Figure A.1 The MATLAB source code for pixel value determination.

An example of pixel value determination showed on command window of MATLAB program as shown in figure A.2. The PSP size 20x25 cm generates 2000x2510 matrix size. The coordinate at center is (1255, 1000).

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```
x=1255
y=1000
Area exposed=600
Initial ROI selected as % of area exposed=0
Final ROI selected as % of area exposed=100
ROI increments as % of area exposed=10
a=868          pixel value at 0% of area exposed
a=869.0507     average pixel value in ROI at 10% of area exposed
a=868.8687     average pixel value in ROI at 20% of area exposed
a=868.4252     average pixel value in ROI at 30% of area exposed
a=864.8466     average pixel value in ROI at 40% of area exposed
a=856.6836     average pixel value in ROI at 50% of area exposed
a=840.2559     average pixel value in ROI at 60% of area exposed
a=823.5452     average pixel value in ROI at 70% of area exposed
a=806.6779     average pixel value in ROI at 80% of area exposed
a=785.8971     average pixel value in ROI at 90% of area exposed
a=763.5340     average pixel value in ROI at 100% of area exposed
```

Figure A.2 An example of pixel value determination using MATLAB source code.

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APPENDIX B
THE DATA OF EXPERIMENTS

Table B.1 The pixel values of the PSP exposed without cassette at 40-120 kVp x-ray beam at selected ROI area up to 100% of exposed area 6x6 cm.

Selected	x-ray beam energy (kVp)								
ROI area	40	50	60	70	80	90	100	110	120
0	860.00	863.00	862.00	859.00	838.00	854.00	851.00	850.00	850.00
10	859.77	862.88	861.91	859.57	837.47	854.64	851.63	850.25	849.07
20	859.68	862.81	861.86	859.51	837.41	854.59	851.58	850.19	849.03
30	859.49	862.63	861.70	859.34	837.26	854.42	851.41	850.01	848.87
40	859.21	862.35	861.43	859.06	837.02	854.13	851.12	849.71	848.58
50	858.46	861.63	860.76	858.40	836.71	853.46	850.46	849.04	847.90
60	856.00	859.32	858.49	856.11	835.86	851.27	848.26	846.86	845.73
70	849.63	853.04	852.21	849.78	832.21	845.10	842.08	840.70	839.55
80	838.97	842.35	841.42	838.85	824.36	834.29	831.20	829.83	828.63
90	820.79	829.96	822.55	822.55	809.98	815.24	812.06	810.78	809.44
100	792.71	795.21	793.89	793.89	787.68	786.72	783.32	782.14	780.92

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Table B.2 The pixel values of exposed PSP plate sizes of 20x25, 35x35 and 35x43 cm without cassette for tube voltage of 80 kVp at various mAs of 10-64 mAs at ROI selected from one pixel area to 60% of exposed area in order to calculate k-values (IC is ionization chamber).

	Plate size					
	20x25 cm		35x35 cm		35x43 cm	
IC	One pixel area	60% of exposed area	One pixel area	60% of exposed area	One pixel area	60% of exposed area
14.75	815	806.04	798	790.21	801	793.71
18.97	826	819.34	831	824.07	831	822.39
24.60	852	844.99	861	854.28	857	849.31
31.09	881	874.39	887	880.16	883	874.39
39.18	912	904.04	912	904.68	907	899.74
50.59	956	946.41	945	937.83	939	930.14
63.67	981	970.92	972	963.96	968	859.67
80.05	1010	999.71	997	989.89	995	986.53
102.97	1023	1019.90	1023	1018.40	1023	1015.40

Table B.3 The comparison of exposures calculated from the various selected ROI area of exposed area from 6x6 cm to 18x18 cm of 80 kVp x-ray beam with the exposures measured with ionization chamber at the same setup in terms of percentage differences.

ROI area as percentage of exposed area	% difference as various exposed areas						
	6x6 cm	8x8 cm	10x10 cm	12x12 cm	14x14 cm	16x16 cm	18x18 cm
0	13.28	11.95	7.80	6.81	3.49	4.23	2.36
10	13.08	11.49	7.75	6.74	3.77	3.91	2.02
20	13.02	11.18	7.30	6.40	3.42	3.57	1.60
30	12.86	10.82	6.86	6.03	3.13	3.20	1.13
40	12.62	10.46	6.53	5.66	2.77	2.79	0.65
50	12.30	10.06	6.19	5.26	2.39	2.32	0.15
60	11.45	9.05	5.84	4.83	1.99	1.82	-0.40
70	7.85	4.65	5.19	4.04	1.53	1.28	-0.98
80	0.50	-5.50	2.02	-0.08	0.62	-0.05	-1.92
90	-11.70	-22.84	-7.42	-13.06	-3.18	-7.18	-5.59
100	-98.37	-98.47	-97.35	-97.45	-96.76	-97.14	-96.91

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Table B.4 The comparison of exposures calculated from PSP plate exposed without cassette at ROI area 80% from 6x6 cm to 18x18 cm exposed area from 40 to 120 kVp x-ray beam with the exposures measured with ionization chamber at the same setup in terms of percentage differences.

	% difference as various exposed areas						
kVp	6x6 cm	8x8 cm	10x10 cm	12x12 cm	14x14 cm	16x16 cm	18x18 cm
40	-38.29	-41.95	-40.97	-43.72	-45.93	-46.77	-46.31
50	-20.66	-22.46	-23.03	-27.01	-28.80	-30.56	-28.41
60	-5.36	-10.34	-10.94	-15.94	-17.74	-17.22	-18.41
70	5.04	2.57	5.93	-0.30	-2.94	-2.60	-3.05
80	10.77	8.24	6.16	5.08	2.57	2.56	0.51
90	16.59	10.21	7.12	0.96	-1.39	-1.89	-2.92
100	18.89	11.37	16.15	9.15	7.04	6.30	5.48
110	19.36	14.99	17.66	8.14	5.83	6.03	4.79
120	19.99	12.85	19.70	14.31	11.98	11.10	10.85

Table B.5 The calculated exposures from the results of average pixel value of PSP plate sizes of 20x25, 35x35 and 35x43 cm at ROI selected from one pixel area to full PSP area in table B.2 **(**IC is ionization chamber**).**

		Plate size					
		20x25 cm		35x35 cm		35x43 cm	
mAs	IC (mR)	One pixel area	Full PSP area	One pixel area	Full PSP area	One pixel area	Full PSP area
10	14.75	15.40	14.21	13.22	12.32	13.58	12.72
12.6	18.97	17.00	16.01	17.78	16.71	17.78	16.46
16	24.60	21.48	20.17	23.29	21.93	22.47	20.97
20	31.09	27.88	26.27	29.43	27.67	28.39	26.27
25	39.18	36.85	34.30	36.85	34.50	35.23	33.00
32	50.59	54.74	50.22	49.58	46.48	46.98	43.38
40	63.67	68.54	62.60	63.21	58.80	60.98	56.57
50	80.05	88.96	81.10	79.15	74.24	77.74	72.03
64	102.97	100.00	97.25	100.00	95.95	100.00	93.39

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Table B.6 The correction factor for energy dependence of 20x25 cm PSP plate exposed without cassette at ROI area 80% from 6x6 cm to 18x18 cm exposed area from 40 to 120 kVp x-ray beam.

	Exposed area							
kVp	6x6 cm	8x8 cm	10x10 cm	12x12 cm	14x14 cm	16x16 cm	18x18 cm	Mean ± SD
40	1.63	1.74	1.70	1.78	1.85	1.88	1.87	1.78 ± 0.08
50	1.26	1.30	1.30	1.37	1.40	1.44	1.40	1.35 ± 0.06
60	1.06	1.12	1.12	1.19	1.22	1.21	1.23	1.16 ± 0.05
70	0.96	0.98	0.94	1.00	1.03	1.03	1.03	1.00 ± 0.03
80	0.90	0.93	0.94	0.95	0.97	0.97	1.00	0.95 ± 0.03
90	0.86	0.91	0.93	0.99	1.01	1.02	1.03	0.97 ± 0.05
100	0.84	0.90	0.86	0.91	0.93	0.94	0.95	0.91 ± 0.03
110	0.84	0.87	0.85	0.93	0.95	0.94	0.95	0.90 ± 0.04
120	0.84	0.89	0.84	0.87	0.89	0.90	0.90	0.88 ± 0.02

Table B.7 The comparison of exposures at various mA measured with 20x25 cm PSP plate and the ionization chamber (IC) at tube voltage from 40 kVp to 120 kVp.

	mR/mAs at 40 kVp			mR/ mAs at 50 kVp			mR/mAs at 60 kVp		
mA	IC	PSP	%diff	IC	PSP	%diff	IC	PSP	%diff
25	0.67	0.70	3.49	1.42	1.43	0.90	2.31	2.38	3.06
100	0.67	0.69	3.40	1.37	1.42	3.85	2.15	2.14	-0.06
200	0.68	0.70	3.05	1.36	1.40	2.55	2.06	2.04	-0.83
250	0.68	0.70	2.34	1.37	1.43	4.00	2.09	2.06	-1.58
500	0.61	0.62	2.26	1.33	1.32	-0.66	2.05	1.97	-3.91

	mR/mAs at 70 kVp			mR/ mAs at 80 kVp			mR/mAs at 90 kVp		
mA	IC	PSP	%diff	IC	PSP	%diff	IC	PSP	%diff
25	3.31	3.25	-1.81	4.37	4.42	1.03	5.57	5.72	2.68
100	3.03	2.98	-1.54	3.90	4.01	2.65	5.05	5.10	1.11
200	2.88	2.82	-2.16	3.67	3.77	2.62	4.73	4.81	1.84
250	2.94	2.88	-1.90	3.73	3.82	2.54	4.80	4.78	-0.42

	mR/mAs at 100 kVp			mR/ mAs at 110 kVp			mR/mAs at 120 kVp		
mA	IC	PSP	%diff	IC	PSP	%diff	IC	PSP	%diff
25	6.85	6.98	1.89	8.25	8.37	1.53	9.73	9.50	-2.34
100	6.15	6.33	2.99	7.31	7.43	1.71	8.50	8.35	-1.78
200	5.68	5.81	2.35	6.87	7.11	3.46	8.16	7.90	-3.20
250	5.76	5.91	2.73	7.01	7.12	1.62	8.37	8.13	-2.89

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