

**MEASUREMENT OF ENTRANCE SURFACE DOSE WITH THE FEMALE
ANTHROPOMORPHIC PHANTOM ON SELECTED DIAGNOSTIC
EXAMINATION USING THERMOLUMINESCENCE DOSIMETRY**

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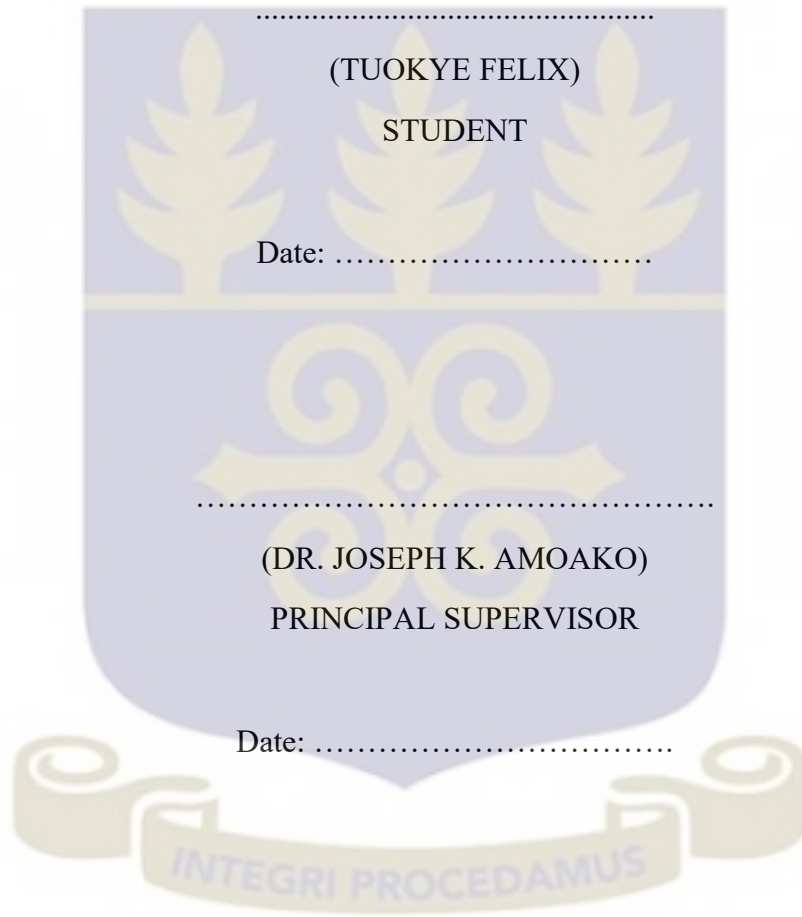
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DECLARATION

I hereby declare that except for the references to other people's work cited, this work is the result of my own research and that it has neither in part nor whole been presented for any other degree elsewhere.



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DEDICATION

This work is dedicated to the Almighty God, my family and all my friends.



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I wish to express my profound gratitude to the Almighty GOD for his protection and strength.

I am extraordinarily grateful to the persons who guided me throughout my studies and the long hard process of the preparation of this thesis; my supervisors, Dr. Joseph K. Amoako, Prof. Cyril Schandorf and Dr. Stephen Inkoom for their patience, advice, support and thoughtful effort throughout my studies.

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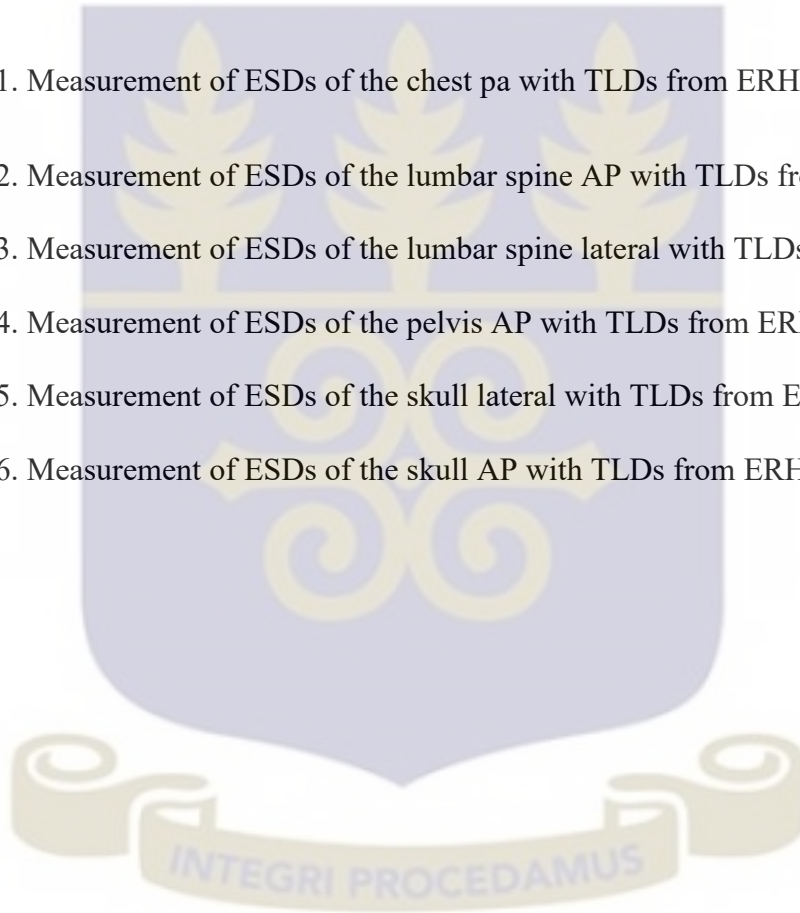


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LIST OF ABBREVIATIONS

TLD	Thermoluminescent Dosimeter
QC	Quality Control
M.PHIL	Masters of Philosophy
SJOH	St. Joseph Orthopedics Hospital
ERH	Eastern Regional Hospital
ESD	Entrance Surface Dose
kVp	Kilovoltage peak
HVL	Half Value Layer

PA	Posterior-Anterior
AP	Anterior-Posterior
LAT	Lateral
REID	Risk of Exposure-Induced Cancer Death
LLE	Loss of Life Expectancy
ALARA	As Low As Reasonably Achievable
ICRP	International Commission on Radiological Protection
IAEA	International Atomic Energy Agency
NEXT	National Evaluation of X-ray Trends
DRLs	Diagnostic Reference Levels
DAP	Dose Area Product
ICRU	International Commission on Radiation Units and Measurement
LDRLs	Local Diagnostic Reference Levels
DR	Digital Radiography
TFT	Thin-film Transistor
CR	Computed Radiography
mAs	Milliampere Seconds
FFD	Focus Film Distance
FSD	Focus Skin Distance
BSF	Backscatter Factor
NDRLs	National Dose Reference Levels
EC	European Commission
WinREMS	Windows Radiation Evaluation and Management System

PC	Personal Computer
DDREF	Dose and Dose Rate Reduction Factor
CEC	Commission of European Communities
NRPB	National Radiological Protection Board
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
BEIR	Biological Effects of Ionizing Radiation
FS	Field Sizes
PAT	Phantom Anatomical Thickness
AvESD	Average Entrance Surface Dose

ABSTRACT

The aim of the study was to measure the entrance surface dose for selected diagnostic X-ray examinations using calibrated thermoluminescent dosimeters on an anthropomorphic phantom. Dose measurement obtained with PCXMC software calculations were used to estimate the stochastic radiation risks and age-dependent mortality rates for subsequent assessment of lifetime cancer risk. Entrance surface dose per examination was estimated from X-ray tube output parameters in two digital X-ray units and a sample of 384 exposures were made. Exposed thermoluminescent dosimeters which were used in the study were read using Harshaw TLD reader Model 6600. The mean entrance surface doses in the two hospitals ranged from 0.2 – 0.3 mGy for chest posterior-anterior, 0.4 – 2.2 mGy for lumbar

spine anterior-posterior, 1.1 – 2.1 mGy for lumbar spine lateral, 0.4 – 4.0 mGy for pelvis anterior-posterior, 0.5 – 0.8 mGy for skull lateral and 0.6 – 0.7 mGy for skull anterior-posterior. The risk of exposure-induced cancer deaths for chest posterior-anterior, pelvis anterior-posterior, skull and lumbar spine are 8.41E-04%, 3.90E-03%, 1.16E-04% and 7.29E-04% respectively. With the exception of chest posterior-anterior examinations, mean entrance surface dose were found to be within the National Radiological Protection Board, Commission of European Communities, International Atomic Energy Agency and United Kingdom reference doses. This work forms part of the national effort to establish National Diagnostic Reference Levels for the selected x-ray examinations.



CHAPTER ONE

INTRODUCTION

1.0. Introduction

This chapter gives the background of the study, the problem statement, research objective, the scope and relevance of the research work. The arrangement of the work is also outlined in this chapter.

1.1 Background of the Study

The increasing use of X-ray for medical diagnosis has shown that diagnostic X-ray examinations represent to a very large extent, the most significant man-made source of exposure to ionizing radiation in the western world (Shrimpton et al, 2000). This observation applies to both developing and developed countries (Faulkner et al, 1999), and has undoubtedly led to an alarming increase in patients' radiation dose (Regulla and Eder, 2005). When these X-ray examinations are conducted appropriately, the medical benefits they provide generally outweigh the risks. If proper precautions are not taken during these examinations, patients may be exposed to excessive radiation without clinical benefits.

Unnecessary radiation exposure to patients, results from the performance of medical imaging procedures when not medically justified (ICRP, 1991). It may also result from the use of radiation dose above what is optimal to meet the clinical need in a given procedure. The quality of the images produced during these procedures depends partly on how much radiation is used, which is under the direct control of the radiographer. The radiographer combines a number of exposure parameters to ensure that doses to patients

are as low as reasonably achievable (ALARA). To a point, using a higher radiation dose can produce a higher image resolution. If the dose is too low, the quality of the image may be poor and as a result a physician may not be able to make an accurate clinical decision. So the foremost consideration during examinations is hinged on two very mutual and fundamental factors: image quality and patient radiation dose.

An optimal radiation dose is one that is as low as reasonably achievable while maintaining sufficient image quality to meet the clinical need. There is a broad agreement that steps should be taken to reduce unnecessary exposure to radiation, given the increasing knowledge of hazard of ionizing radiation (Brenner and Hall, 2007). The results of several years of research in radiobiology have shown that radiation can cause cancer and other genetic effects (Bushberg et al, 2002). Over the years, the biological effects of ionizing radiation have led to increased efforts to obtain radiographs of acceptable image quality and of diagnostic value from doses that are compatible with safety and health in compliance with ALARA principle (UNSCEAR, 2000). The radiation protection programme for patients undergoing X-ray examinations is governed by the principles of justification and optimization, including the consideration of diagnostic reference levels (ICRP, 1990).

Diagnostic X-ray examination is justified if the clinical benefit outweighs the risk associated with the exposure to ionizing radiation. Once a medical exposure has been justified, the principle of optimization is applied – that is, the dose of radiation which is delivered to the patient must be kept as low as reasonably achievable (ALARA) but high enough to obtain required diagnostic information, taking into account economic and social factors (ICRP, 1991; IAEA, 1996). This value is interpreted as being the lowest dose possible, which is consistent with the required image quality, necessary for obtaining the

required diagnostic information. It is important to note that there is no dose limits for patients undergoing X-ray examinations (Marcelo and Elisabeth, 2009). This is based on the fact that there is no safe level of exposure. In other words even the smallest exposure has some probability of causing a stochastic effect, such as cancer. Hence, the principle of optimization is an essential control mechanism used to shield patients from unnecessary radiation exposure.

The concept of diagnostic reference levels (DRLs) was recommended for use in radiology by both the International Commission on Radiological Protection (ICRP) and International Atomic Energy Agency (IAEA), following the results of radiation dose survey conducted by Shrimpton et al. (1986) and Faulkner and Corbelle (1998). The result showed a wide variation in patient dose levels for the same X-ray examination up to a factor of 100. On the same vein the result of the study conducted by the Nationwide Evaluation of X-Ray Trends (NEXT) survey program in the United States also, show that patient doses in x-ray examinations are high and vary from one facility to the next (Gray et al, 2005). Other studies reported wide variations in patient dose for the same radiographic examinations within and among hospitals in the United Kingdom and in Europe (Johnston and Brennan, 2000; Carroll and Brennan, 2003).

Diagnostic reference levels (DRLs) are conventionally set in dose quantities that are relatively readily available to the user of X-ray equipment. In conventional radiography, the most important parameters measured are the total Dose Area Product (DAP) and the Entrance Surface Dose (ESD) (Waltenburg et al, 2010). Entrance surface dose is defined as the absorbed dose in mGy measured in air at the intersection of the axis of the X-ray beam and the patient's skin surface or a phantom; it includes back- scatter

rays. It is a quantity that can be measured directly and can easily be compared with previous measurements and with that obtained in other practices and countries. Another reason for evaluating ESD is that the dose is greatest at the surface where radiation enters the body of the patient and the skin is therefore the main organ for which there is a possibility of deterministic effect (skin burn). The ESD has been recommended by the International Atomic Energy Agency (IAEA) in 1995 and the European Union in 1997 as the dose signifier for guidance level in diagnostic radiography (IAEA, 1995; Commission of European Communities, 1997). International guidance on patients dosimetry techniques for X-rays used in medical imaging was published by the International Commission on Radiation Units and Measurements in ICRU report 74 (ICRU, 2005).

1.2. Statement of Problem

Several international organizations have recommended that for the optimization of protection of the patient, imaging facilities should work towards establishing diagnostic reference levels for imaging procedures consistent with acceptable image quality for diagnosis.

Under various donor agency projects, several imaging facilities in Ghana have acquired new equipment and accessories without the establishment of diagnostic reference levels for imaging procedures as part of the institutional effort to incorporate quality assurance and quality control programmes for the protection of the patient. .

This study seeks to assist the two facilities to establish local DRLs as basis for monitoring the effectiveness of the protection of the patient at these facilities over time.

1.3. Objective of the Study

The objective of this study is to estimate the entrance surface dose for phantom undergoing common X-ray examinations of the chest (PA), skull (AP/Lateral), lumbar spine (AP/Lateral) and pelvis (AP) in two diagnostic radiology centers in the Eastern Region of Ghana using thermoluminescence dosimeters and establish local diagnostic reference levels (LDRLs) as part of the national effort to establish national DRLs for the selected examinations.

1.4. Specific Objectives

- a) To undertake comprehensive quality control on X-ray machines at the two hospitals
- b) To obtain entrance surface dose values for adult phantom undergoing commonly performed diagnostic examinations in Ghana
- c) To compare dose levels obtained from studies in the two hospitals with international reference dose levels
- d) To estimate radiation risk to organs of dose delivered to patients at the diagnostic examinations.
- e) To make appropriate recommendations from the findings of the research work

1.5. Scope of the Study

The study considered phantom to simulate patients undergoing chest (PA), skull (AP/Lateral), lumbar spine (AP/Lateral) and pelvis (AP) X-ray examinations at St. Joseph Orthopedics Hospital and Eastern Regional Hospital.

1.6. Justification and Relevance of the Study

The establishment of regional, national and local diagnostic reference levels (DRLs) is part of a global effort to address the recommendation in the ICRP Report 103 (ICRP, 2007). Diagnostic reference levels is a tool for optimization of protection of the patient in diagnostic imaging procedures while ensuring that acceptable image quality is not lost.

The outcome of this study will enable appropriate steps to be taken for the two facilities to undertake the necessary remedial actions where needed to be compliant with national and international standards.

The two facilities will have local DRLs available to use to monitor and evaluate progress of imaging performance several years into the future.

1.7. Organization of Thesis

Chapter one deals with the background of the study, the problem statement, objectives, justification and relevance of the work, scope and limitation. Chapter two contains literature review relevant to the research work. Chapter three describes the research materials and methods used to conduct the study. Chapter four outlines the results obtained and subsequent discussion on the findings, Chapter five gives the conclusions of the study, recommendations and suggestions for further research work.

CHAPTER TWO

LITERATURE REVIEW

2.0. Introduction

This chapter highlights the relevant literature review pertinent to the topical area of the study. It covers, overview of digital radiography; factors affecting patient dose; variables affecting the selection of technique factors; dose measurements methods; radiation protection and review of similar work done.

2.1. Overview of Digital Radiology

Digital radiography is a form of X-ray imaging, where digital X-ray sensors are used instead of traditional photographic film. Advantages include time efficiency through bypassing chemical processing and the ability to digitally transfer and enhance images. Digital imaging took over conventional film-screen technology about 30 years ago. This is primarily due to the perceived advantages of radiation detection technology, digital image processing, archiving, optimization of image acquisition and display independently (Honey and Mackenzie, 2005). The wide dynamic range of digital system gives a great advantage in imaging of widely different attenuating structures (Schaefer-Prokop, 2009). Digital radiography (DR) are digital technologies widely spread in most healthcare institutions. Digital radiography technology converts X-rays into electrical charges by means of a direct readout process using thin-film transistor (TFT) arrays. Depending on the type of X-ray conversion used, DR systems can be further divided into direct conversion with a flat-panel detector based on amorphous selenium (a-Se) and indirect conversion with a two stage

technique based on scintillator such as caesium iodide (CsI) and a photodiode array of amorphous silicon (a-Si) (Lanca and Silva, 2009). Digital radiography flat-panel systems due to their higher detective quantum efficiency compared to CR have potential for dose reduction.

2.2. Factors Affecting Patient Dose

Some of the relevant factors that affect doses received by patients undergoing diagnostic radiologic examinations include exposure parameters, factors modifying these exposure parameters and dosimetry technique employed during dose measurement (Edmond, 1984).

2.2.1. Exposure Factor Selection

The entire focus of radiographic technique is to optimize patient dose and produce the best possible image quality. Three technical factors that are used to achieve this purpose are mA, time and kV (Parry et al, 1999).

2.2.2. Milliampere-seconds (mAs)

The milliamper (mA), is a measure of the quantity of electrical current flowing through a circuit. It is a rate representing the number of electrons passing down a wire per second. The higher the mA setting, the greater is the flow rate of electricity passing through the filament in the X-ray tube cathode.

The radiographic term mAs is an electrical term derived from the product of mA and the time. They refer, respectively, to the rate of electrical current and the total amount of electricity used during an exposure. It is the primary electric control over x-ray exposure. One reason the mAs is the preferred parameter to control the quantity of exposure is that it only affects the quantity of exposure, whereas the use of other parameters may have an undesirable effect on things we do not wish to alter. For example, kVp can be used to increase or decrease the exposure, but it also changes the penetration characteristics of the X-ray beam and the subject contrast present in the remnant beam, things we may not wish to tamper with. The total mAs used to produce a radiograph is directly proportional to patient exposure. Twice the mAs will deliver twice the ESD to the patient. Radiographically equivalent increases in kVp deliver less exposure to the patient, although they alter the image contrast with film-based system (Sprawls, 1993).

2.2.3. Kilovoltage-peak (kVp)

Kilovoltage (kVp), is a measure of the electrical force or pressure behind a current of electricity, which causes it to flow. It is a measure of electrical energy. Whenever a potential difference exists between two points in a conductor, a current of electrons will flow through the conductor toward the negative charge.

The greater the potential difference, the more “pressure” is exerted on the electrons to flow, the greater the energy pushing the current, and the higher kV will be measured. Whereas mAs has been described as a measure of electrical quantity, kV is a measure of electrical quality. The main purpose for adjusting the kVp is to set the penetration level of the x-ray beam. The percentage of x-ray penetration through any particular tissue or patient

is a direct function of the average energy of the X-rays. This average energy is pulled upward when the peak energy is increased. But, an increase in kVp also results in more bremsstrahlung x-rays being produced within the x-ray tube anode, so that the quantity as well as the quality of the X-rays is increased. This is undesirable side-effect for the radiographer when the intent is mainly to adjust penetration. Generally, the radiographer prefers to use mAs to control x-ray quantity because mAs is directly proportional to output and does not affect other aspects of the beam. But, increased output from the x-ray tube cannot be avoided at higher kVp's, and must be taken into account when considering the total exposure that penetrates through the patient to the image receptor (Sprawls, 1993).

When it comes to reducing technique, it is more in the patient's interest to decrease the mAs rather than the kVp, since there will be a proportional reduction in patient dose. Furthermore, reductions in kVp can result in inadequate penetration through the anatomy and result in repeated exposures.

The x-ray tube kVp is most critical of the quality control parameters because a small error of this variable will have a greater effect on the final radiographic image than an equivalent variation in any of the other parameters such as tube current (mA), exposure time and focus to film distance. The X-ray intensity reaching the image receptor after the beam passes through the patient varies approximately as the fifth power of kVp. The kVp affects not only the intensity reaching the image receptor but also the subject contrast of the image.

2.3. Variables Modifying Selection of Technique Factors

2.3.1. Focus Film Distance (FFD)

The distance from the x-ray tube to the image receptor is very important because it has substantial influence on both the image qualities and exposure level. X-rays diverge as they are emitted from the focal spot, and, proceeding in straight paths, cover an increasingly larger area with lessened intensity as they travel from their source. The area over which the force or radiation spreads out increases as the square of the distance and the intensity of exposure diminishes as the FFD is increased (Bushbery et al, 2011). The ESD is therefore inversely proportional to the square of the FFD, for the same kV and mAs, and the dose reaching the surface of the patient is expected to be increased when the FFD is short.

2.3.2. Generators Waveform

Higher-power generators like the 3-phase or high-frequency generators are designed to be electrically more efficient in producing x-rays, generating more milliroentgen (mR) per mAs, so that the reduced techniques are merely compensating for a higher exposure rate. A slight savings in patient exposure is achieved because these generators also produce higher energy levels at a particular kVp setting. Decrease in overall exposure to patients is normally attained by high-power equipment. Typical techniques for these machines employ much lower kVp settings. It is in the interest of the patient to decrease the mAs rather than the kVp during radiographic examinations. By using lower mAs values rather than lower kVp on constant potential generator mobile units, patient dose could be significantly lowered (Parry et al, 2002).

2.3.3. Filtration

Filtration is the process of shaping the X-ray beam to increase the ratio of photons useful for imaging to those photons that increase patient dose or decrease image contrast. Diagnostic X-ray beams are polychromatic (i.e they are composed of photons that have a whole spectrum of energies). As polychromatic beam passes through a patient, most of the lower energy photons are absorbed in the first few centimeter of tissue, and only the higher energy photons penetrate through the patient to form the radiographic image (Parry et al, 2002). Because the patient radiation dose depends on the number of absorbed photons, the first few centimeter of tissue receive much more radiation than the rest of tissues in the patient. These tissues can be protected by absorbing the lower energy photons from the beam before they reach the patient by interposing a filter material between the patient and the X-ray tube. Filters are usually sheets of metal and their main function in diagnostic radiology is to reduce the patient radiation dose.

There are two main types of filtration, inherent filtration and added filtration. Inherent filtration is the type resulting from the absorption of X-ray as they pass through the X-ray tube and its housing. The materials responsible for inherent filtration are the glass envelope enclosing the anode and the cathode, the insulating oil surrounding the tube, and the window in the tube housing. Inherent filtration is measured in aluminum equivalent which represent the thickness of aluminum that would produce the same degree of attenuation as the thickness of the material in question. Added filtration result from absorbers placed in the path of the x-ray beam (Parry et al, 2002). The major disadvantage of filtration is a reduction in the intensity of the X-ray beam. Filters absorb some photons at all energy levels and we must compensate for the loss of higher energy photons by

increasing exposure factors (mAs). Even when it is necessary to increase exposure because of filtration, the patient receives less radiation than he would from an unfiltered beam. The X-ray tube produces more photons but the filter absorbs many of them, and the total number reaching the patient actually decreases.

A minimum of 2.5 mm aluminum equivalency in total filtration is required in all X-ray equipment capable of operating above 70 kVp (CEC, 2003). Slab filters that have been placed in or above collimators should not be removed, as they are part of this required total filtration. Proper x-ray beam filtration is critical to minimizing patient dose, because it removes from the X-ray beam low-kV X-rays that would otherwise only be absorbed within the patient, and have no diagnostic value since they never reach the image receptor anyway (Parry et al, 2002).

2.3.4. General Patient Condition

Thicker body parts, casts, and additive diseases require more exposure factors, and are outside the control of the radiographer unlike the mAs, kV, FFD etc. The condition of the patient is something the radiographer has almost no control over, but must be aware of and take into account when selecting the technical factors for an exposure. Despite the many natural variations in body type and shape among humans, it is possible to establish certain patterns of thickness measurement for radiographic purposes that may conform to what may be termed average thickness ranges. Such measurements can be standardized and are an important means of standardization for radiographic exposures. Apart from the thickness of a body part, the attenuation of X-rays as they pass through it is a function of both the molecular or average atomic number of the tissues and the average physical

density of the tissues (Callisen et al, 1980). X-ray beam absorption due to combination of part thickness and atomic number is exponential, while absorption due to physical density is only proportional and thus requires huge discrepancies to make a difference (Maillie et al, 1982).

Radiographs taken after a broken limb has been set and casted are called post reduction radiographs. Generally, most full plaster casts require a doubling in mAs, or a 12–15 percent increase in kVp (Carroll, 2011). Abnormal conditions which lead to an increase in fluid, bone, or metal are, for radiographic purposes, considered as additive conditions. They require increased technique factors in order to attain proper exposure at the image receptor. Age is another factor that has influence on the exposure factor used during radiographic procedures. Throughout life there is a constant flux in bone mineralization. In infants and very young children, calcification of bones is very slight, and reduced kVp will provide proper penetration. During the growth period, bone formation is more rapid than resorption. During middle age, bone formation and bone resorption are in balance. In later life, resorption exceeds bone growth and mineralization decreases. There is also some atrophy, or loss of water and minerals, from soft-tissue organs. Lower kVp levels are required to avoid over penetration.

2.3.5. Grids and Image Receptor

Radiographic grids consist of lead foil strips separated by X-ray transparent spacers. They are used to absorb scatter radiation and improve radiographic image contrast. The grid ratio is defined as the ratio of the height of the lead strips to the distance between them, and it is the simplest way of characterizing a grid (Bushberg, 1994). Grids come in

two patterns; linear, and crossed. Crossed grids consist of two superimposed linear grids. Grid selection involves a compromise between film quality and patient exposure. High ratio grids produce film with better contrast at a cost of increased patient exposure. High-ratio grids absorb more radiation, and require increased radiographic techniques in order to maintain sufficient signal to the image receptor. In the interest of minimizing patient exposure, the minimum grid ratio which provides sufficient clean-up of scatter radiation should be used.

The image receptor used in screen film radiography is the X-ray films. The X-ray films are classified as follows:

Speed class 100

Speed class 200

Speed class 400

Speed class 600

Speed class 800

The higher the speed classes the more the sensitivity of the film and the less the radiation dose to patient. Materials used for the front panels of cassettes which houses both the intensifying screens and the film must be as radiolucent as possible while still providing structural protection. Added layers in front of the actual active matrix array of detectors absorb more radiation and necessitate higher techniques. The greater the overall efficiency of the image receptor, the more patient exposure is saved.

2.3.6. X-ray Beam Restrictors

X-ray beam restrictor is a device that is attached to the opening in the X-ray tube housing to regulate the size and shape of X-ray beam. There are three types of X-ray beam restrictors, aperture diaphragm, cones and collimators. Their basic function is to regulate the size and shape of X-ray beam. Closely collimated beams have two advantages over larger beams. First, a small area of the patient is exposed and this result in decreased patient exposure. Second, well collimated beams generate less scatter radiation and thus improve image quality. By decreasing the amount of scatter radiation, collimator also affects exposure factors. As the X-ray field size is decreased, the exposure factors must be decreased to maintain a constant film density.

2.3.7. Intensifying Screens

Sensitivity of x-ray films to direct X-rays is very low and radiation doses that will be required would be prohibitively high for general application. On this note intensifying screens are used in film screen radiography to influence dose efficiency and improve image quality. With the traditional calcium tungstate screen, a dose reduction of 5-25 times when compared to non-screen films was achieved but with the current rare earth phosphors a further 50% dose reduction is possible (Agwu, 2005). This dose reduction enables short exposure times to be utilized to minimize the blurring effects from patient's motion. A good estimate of this dose reduction is represented by the intensification factor of the screen. Intensification factor is defined as the ratio of X-ray exposure required to produce a net density of 1.0 on a film without intensifying screen compared to that required to produce the same density on the same film without intensifying screen (Parry et al, 2002).

The practical significance of this factor is that it is a guide in the choice of exposure factors when transferring from no-screen film to a screen film combination. The value of the intensification factor also varies from one film screen combination to the other based on speed class of the film. Intensifying screens can be graded or classified into the following speed classes;

- a. Speed Class 100; these are the Slow screens or high definition screens a thin layer and relatively small crystals are used; detail is the best, but speed is slow necessitating a higher dose of ionizing radiation.
- b. Speed Class 200; these are the medium screens - medium thick layer of medium sized crystals in order to provide compromise between speed and definition.
- c. Speed Class 400; these are the Fast screens - thick layer, and relatively large crystals used, maximum speed is attained but with some sacrifice in definition.

There are three types of intensifying screens:

Standard - slow screens

Rare earth - fast screens

Combination

Standard screens use calcium tungstate phosphors, while rare earth screens use gadolinium or lanthanum phosphors. The commercial name for rare earth screens is Lanex. Rare earth phosphors are more efficient at converting X-rays to visible light thus reducing the radiation further to the patient. The manufacturers name and the type of screen are printed on the one side of the screen and this information appears on the radiograph. The intensifying screen is placed in a cassette in close contact with a film. The visible light

from its fluorescent image will add to the latent image on the film. Its function is to reinforce the action of X-rays by subjecting the emulsion to the effect of light as well as ionizing radiation. The benefit is the reduction in dose of ionizing radiation to the patient.

2.4. Dose Measurement Methods

2.4.1. Entrance Surface Dose.

Measurement of ESD is usually required for a specific type of radiograph if deterministic effects are possible. Entrance surface dose can be measured directly on the patient with TLDs or can be derived from measurements of incidence absorbed dose (ID) by multiplying by the backscatter factor.

2.4.2. Determination of ESD from TLD Measurements

Thermoluminescent dosimeters are considered as the gold standard for determination of the entrance surface dose in practice. Measurements are made with thermo-luminescent dosimeters, TLDs, attached to the patient or phantom at points where the x-ray beam enters the patient. TLDs are read in a standard manner and the value read is used as an estimate of the ESD received by the patient. If correctly calibrated to measure air kerma free in air, the TLD should give a direct reading of the entrance surface dose, and no correction is needed for back scattered radiation or distance from the tube focus (ICRP, 2007).

2.4.3. Calculation of ESD from Tube Output Data

Entrance surface dose may be calculated in practice by means of knowledge of the tube output (Toivonen, 2001). The relationship between X-ray unit current time product (mAs) and the air kerma free in air is established at a reference point in the X-ray field at 80 kVp tube potential. Subsequent estimates of the ESD can be done by recording the relevant parameters (tube potential, filtration, mAs and FSD) and correcting for distances and back scattered radiation according to the following equation (Toivonen, 2001).

$$\text{ESD} = \text{OP} \times \left(\frac{\text{KV}}{80}\right)^2 \times \text{mAs} \times \left(\frac{100}{\text{FSD}}\right)^2 \times \text{BSF} \quad [2.0]$$

where OP is the tube output per mAs measured at a distance of 100 cm from the tube focus along the beam axis at 80 kVp, kV is peak tube voltage (kVp) recorded for any given examination (in many cases the output is measured at 80 kVp, and therefore this appears in the equation as a quotient to convert the output into an estimate of that which would be expected at the operational. kVp. The value of 80 kVp should be substituted with whatever kVp the actual output is recorded at any given instance). mAs is the tube current-time product which is used in any given instant. FSD is the focus-to-patient entrance surface distance and BSF is the backscatter factor.

2.4.4. Calculation of ESAK and ESD from Tube Output Data

The relationship between x-ray unit current time product (mAs) and the air kerma free in air is established at a reference point in the X-ray field for the range of tube potentials encountered. Subsequent estimate of the entrance dose can be done by recording the relevant parameters (tube potential, filtration, mAs and FSD) and correcting for

distances (and back scattered radiation in case of ESD estimation) as implied in the formula below (Saxebol and Olerud, 1996).

$$\text{ESAK} = K_{\text{air}}(100\text{cm}) \cdot \left(\frac{100}{\text{FSD}}\right)^2 \quad [2.1]$$

$$\text{ESD} = (\text{ESAK}) \cdot (\text{BSF}) \quad [2.2]$$

2.4.5. Determination of ESD from DAP Measurements

In interventional radiology, the use of DAP to estimate ESD may be desirable in many cases especially when the department do not have access to TLD's, which are often used for this purpose. Entrance skin dose (ESD) can be calculated from the knowledge of DAP (Mac Parland, 1998).

$$\text{ESD} = \left(\frac{\text{DAP}}{A_{\text{II}} \text{II}\phi, \text{FID}}\right) \left(\frac{\text{FID}}{\text{FSD}}\right)^2 \times \text{BSF} \times \left(\frac{\mu_{\text{tr}}}{\rho}\right)_{\text{air}}^{\text{tissue}} \quad [2.3]$$

Where A_{II} is the field area measured at FID. Due to positive beam limitation, A_{II} has an explicit dependence upon $\text{II}\phi$ and FID. BSF is the backscatter factor. $\left(\frac{\mu_{\text{tr}}}{\rho}\right)_{\text{air}}^{\text{tissue}}$ is the ratio of the mass energy conversion coefficient tissue to air. For all diagnostic x-ray energies, the mass energy absorption coefficient ratio of tissue to air is ~ 1.06 .

2.4.6. Thermoluminescent Dosimeter

Thermoluminescent dosimeters (TLDs) often are used for dose measurement in plain-film examinations. They can be made of different materials including lithium fluoride

or lithium borate; more recent types are copper manganese doped to increase sensitivity. The sensitivity of particular TLD material is defined as the thermoluminescence signal strength per unit absorbed dose. Once exposed, TLDs are subjected to a complex cycle involving heat within a reader, light is emitted and measured, and dose calculated using a predetermined calibration figure. These TLDs are desirable because of the crystal's tissue equivalent property as well as other reasons as listed below;

- a. Response is linear with dose over a wide range.
- b. Sensitivity is almost energy independent.
- c. Adequate sensitivity is achieved in very small volume.
- d. The TLD's are small and of low atomic number therefore are unlikely to obscure diagnostic information.

More importantly, TLDs records backscatter radiation that can increase the radiation dose to the patient up to 40%. (NRPB, 1992). They are small, although they come in range of sizes. They are easily attached to patient or phantom, and for most plain film examination excluding mammography, do not have any impact on the image. They are also inexpensive and readily available.

TLDs should not be used for mammography. First, because of the low X-ray energy levels employed, it is possible that the TLD may be visible on the image and obscure important detail. Second, because the radiation dose decreases rapidly as the beam progresses from the entrance surface to the exit surface of the breast, a single entrance surface measurement is not sufficiently representative of the dose delivered to the breast.

The accuracy of the TLD is subject to uncertainty arising from a variety of sources including:

1. TLD signal fade.
2. Variations in TLD reader performance.
3. TLD calibration method.

2.4.7. Dose Area Product (DAP)

Apart from the use of TLD technique in the estimation of entrance surface doses, dose area product (DAP) meters can also be used to measure the ESD for patient undergoing conventional X-ray examination. The DAP (Gycm^2) is defined as the air kerma averaged over the area of the X-ray beam in a plane perpendicular to the beam axis, multiplied by the area of the X-ray beam in the same plane. Dose Area Product meters are large-area, transmission ionization chambers and associated electronics. In use, the ionization chamber is placed perpendicular to the beam central axis and in a location that completely intercept the entire area of the X-ray beam. The DAP in combination with information on X-ray film size, can be used to determine the average dose produced by the x-ray beam at any distance downstream in the X-ray beam from the location of the ionization chamber. A recent modification of the ionization chamber design used in DAP meter has resulted in an instrument that measures both DAP and the dose delivered by the X-ray beam (Bushberg, 2011). This design effectively combines data from a small ionization chamber that is completely irradiated by the beam and independent of the collimator adjustments with the conventional DAP meter.

Although DAP meters may have the advantage that patient- specific dosimeters are not required, thermoluminescence dosimeters are of choice in this study because DAP meters do not measure backscattered radiation. This stems from the fact that the measuring device is located at the X-ray tube rather than the patient or phantom as the case may be. The unit remain in place for all patients being imaged by the X-ray unit but readout is automatically generated after each exposure. The meters are difficult to calibrate and maintain. Large changes in the DAP meter response can occur over time, particularly if meters are adjusted for couch transmission factors (ICRP, 2007). Calibration should be done in the field after any changes that might alter the DAP and at least annually. DAP meters do not measure skin dose, which is important in high-dose examinations such as cardiac and vascular interventional procedures (Bushberg, 2011).

2.5. Radiation Protection

The goal of radiation protection in diagnostic radiology is to prevent deterministic effects by ensuring that radiation doses are kept well below relevant threshold doses and to minimize the probability of stochastic effects. To accomplish this goal, radiation protection is guided by radiation protection principles and radiation protection actions. Radiation protection actions involve the use of time, shielding and distance to protect patients during diagnostic procedures. Radiation protection principles deal with the concepts of justification or positive net benefit, optimization and dose limitation (ICRP, 1990). Justification "provides an essential moral stance for the intelligent use of radiation," (Wolbarst, 1993). It is important to note that there are no dose limits for patients undergoing diagnostic x-ray examinations. This is because the goal of radiation protection is to shield

patients from unnecessary exposures, and the principle of optimization is the essential control mechanism used for this purpose.

Optimization principle: This principle is used to protect patients from unnecessary radiation exposure by using a dose that is as low as reasonably achievable (ALARA). One tool used in radiology to optimize radiation protection of patients is the diagnostic reference level (DRL). It is important to note that optimization also must address image quality, so that dose optimization procedures do not compromise the image quality needed to make a diagnosis. Optimization is one of the radiation protection principles that ensure that radiation doses to patients during diagnostic radiologic examinations is kept to a minimum in accordance with the ALARA principle while maintaining the diagnostic quality of the examination (ICRP, 2007). To achieve this, the following factors are considered:

- a. Time: Time of exposure should always be minimized.
- b. Distance: The distance between the patient and the radiation source should be maximized. The longer the distance the lower the dose.
- c. Shielding: Absorber material should be used to cover part of the patient that is not under direct examination.

Another factor that needs to be considered is the performance of radiographic equipment. These include choice of screen film combination and the preparation of automatic exposure control devices to suit its characteristics. Tube potential determines the photon energies in the X-ray beam, with the selection involving a compromise between image contrast and the dose to the patient. Allied to this is the choice of anti-scatter grid, as a high grid ratio effectively removes the larger components of scatter when using high tube potentials. However a high grid ratio attenuates the X-ray beam more heavily. Another

factor which can reduce patient dose is the use of copper filtration to remove more low energy X-rays. Regular survey of patient dose and comparisons with diagnostic reference levels that provides a guide representing good practice enable facilities to which doses are higher to be identified. Causes can be investigated and changes investigated to address any shortfalls. Application of these methods has led to systematic reduction in dose in many countries (Martin et al, 1999).

Another significant factor in reducing patient exposure is to ensure that only necessary examinations are performed with good technique. It is possible, for example, to obtain a series of diagnostically-acceptable radiographs and have the patient exposures vary wide because of choice of technique and loading factors used. It is the responsibility of the radiographer to be aware of this and to know how to carry out a prescribed examination with the lowest possible dose to the patient. In order to ensure that radiation dose to patients are kept as low as reasonably achievably the radiographer should;

- a. Not perform any examination which has not been prescribed by a qualified medical practitioner.
- b. Use of an anti-scatter grid or air gap between the patient and the image receptor.
- c. Avoid the use of extremely short to image distance as this can lead to unnecessary high skin dose.
- d. Use the highest X-ray tube voltage which produces images of good quality.
- e. Use automatic exposure control devices designed to keep all irradiations and repeat irradiations to a minimum.

- f. Collimate the primary X-ray beam to within the size of the image receptor in use and only expose the critically relevant region of interest. This has the added benefit of simultaneously of improving image quality and lowering dose.
- g. Apply shielding where appropriate and practicable to limit the exposure of body tissues. It is particularly important that special effort be made to protect the blood forming organs, gonads, and thyroid of children. The lens of the eye and breast should also be protected. Note that when the use of shielding will obscure desirable information relevant to the examination, the use of such shielding should be discouraged.
- h. Evaluate the resulting images to verify that the techniques being used are producing diagnostic quality images and that the X-ray equipment is functioning correctly.
- i. Avoid the necessity of retakes, it is particularly important before taking a long series of images that a single preliminary image of the series should be taken to verify correctness of settings.

The above mentioned practical steps should be taken by the radiographer to ensure adequate protection of the patient without loss of image quality acceptable for diagnosis.

2.6. Review of Similar Research Work

Medical physicists have devoted much effort in recent years towards reduction of patients' doses in diagnostic radiology through optimization. Through these efforts, substantial reductions in radiation doses to patients resulting from radiographic procedures have been achieved in many countries (Martin et al, 1999). A useful background for such efforts is the knowledge of radiation doses to patients undergoing common X-ray

examinations. This knowledge was made possible in some countries where National Diagnostic Reference Levels (NDRLs) have been established through surveys of patients' doses in diagnostic radiology. In the United Kingdom the dose survey that led to the establishment of national DRLs was carried out in mid 1980s. Some other countries such as Switzerland (Aroua et al, 2004), Brazil (Marcelo and Elisabeth, 2009), and Slovenia (Skrk et al, 2006) have also established NDRLs, and reviewed it at various times.

Related literatures on measurement of entrance surface dose received by patients using TLDs are as follows:

(a) Schandorf and Tetteh (1998) determined the levels of dose and dose distributions for adult patients undergoing five selected common types of X-ray examinations in Ghana using TLDs attached to the skin where the beam enters the patient. To assess the performance of each X-ray units surveyed, the mean of the entrance surface dose for patients whose statistics were close to a standard patient (70 kg weight and 20 cm AP trunk thickness) were compared to the European Commission (EC) guideline values for chest PA, lumbar spine AP, pelvis/abdomen AP and skull AP examinations. The third quartiles dose values were 1.3 mGy, 14.5 mGy, 12.0 mGy and 7.9 mGy for chest PA, lumbar spine AP, pelvis/abdomen AP and skull AP, respectively. Analysis of the data showed that 86%, 58%, 37.5% and 50% of radiographic units delivered a mean dose greater than the EC guideline values for chest PA, lumbar spine AP, pelvis/abdomen and skull AP, respectively. This suggests that the radiographic departments should undertake a review of their radiographic practice in order to bring their doses to optimum levels. Wide variations in patient dose for the same type of X-ray examination have been evident from various

international dose surveys. Reference dose levels provide a framework to reduce this variability and aid in the optimization of radiation protection.

(b) Johnston and Brenann (2000) studied patient doses in the most common X-ray examinations: chest, abdomen, pelvis, and lumbar spine. The aim of the study was to establish, for the first time, a baseline for national reference dose levels in Ireland. Measurements of entrance surface dose using TLDs for these four x-ray examinations were performed on 10 patients in each of 16 randomly selected hospitals. This represented 42% of Irish hospitals applicable to the study. Results have shown wide variation of mean hospital doses, from a factor of 3 for an anterior-posterior lumbar spine to a factor of 23 for the chest x-ray. The difference between maximum and minimum individual patient dose values varied up to a factor of 75. Reasons for these dose variations were complex but, in general, low tube potential, high mAs and low filtration were associated with high-dose hospitals. The study also demonstrated lower reference dose levels of up to 40% when compared with those established by the UK and the European Commission for four out of six projections. Only the chest x-ray exhibited a similar reference level to those established elsewhere. This emphasizes the importance of each country establishing its own reference dose levels that are appropriate to their own radiographic techniques and practices in order to optimize patient protection.

(c) Ogundare (2004) used TLDs to measure the ESDs of patients undergoing pelvis, abdomen and lumbar spine diagnostic x-ray examinations in Nigeria. A total of three public hospitals and 171 patients were included in the investigation. The ages of the patients involved were from 40 years to 85 years, while their weights ranged from 64 kg to 73 kg. Mean, median, first and third quartiles of ESDs were reported. The results showed that in

most cases, for each of the examinations, the individual ESD values were found to be comparable with, and higher than, those from Ghana and Tanzania, respectively. The mean ESD values were also found to be within the range of mean ESD values that have been previously reported from countries outside Africa. When compared with the European Commission (EC) reference values, the mean ESDs were found to be below the reference values in only two of the hospitals. The ranges found in the work were high and this indicates more attention needs to be given to X-ray facilities in the country. This also suggests that radiographic departments need to review their radiographic practices in order to bring their doses to optimum levels. Effective doses were also calculated from the ESD values. The mean effective doses were found to be generally low when compared with those found in the literature from other countries including two African countries. The radiographic parameters used for all the patients were also compared with the European Commission criteria. It was recommended that the tube filtration at one hospital be increased. The importance of good regulatory activities and trained personnel is stressed in the work. The data provided in the work was stated to be useful for the formulation of national guidance levels.

(d) Shahbazi Gahrouei (2006) estimated the radiation doses received by patients in diagnostic radiology sections in hospitals under control of Chaharmahal and Bakhtiari Medical Sciences University, in the south west of Iran. Shahbazi Gahrouei (2006) measured the ESDs for the most routine types of x-ray procedures in radiology centers as part of on-going dose reduction program. Geiger-Muller and TLDs were used to measure entrance surface doses for four common radiographic views in six hospitals (7 x-ray machines). The ESD was measured on 20 randomly selected patients (male and female)

for each x-ray examination. Patients were not exposed to any additional radiation and the radiographs were used for diagnostic purposes. The entrance surface doses for the PA and lateral chest x-ray examinations were found to be in the range of 0.22-1.45 and 0.34- 4.90 mGy, respectively. The ESD values for the AP or PA skull and LAT skull were in the range of 2.55-8.45 and 2.85-9.12 mGy, respectively. Most of the ESD measured doses were slightly greater than the ICRP and NRPB reference doses. The study recommended that there is the need for quality assurance (QA) programs to be undertaken to avert considerable cost and high patient doses.

(e) Ujah (2012) used TLD technique to measure the amount of radiation received by patients or phantoms during routine Posterior-anterior (PA) chest x-ray examination in Federal Medical Centre and Bishop Murray Hospital in Makurdi, Benue State. The results obtained were compared with the diagnostic reference level set by IAEA and ICRP. At Federal Medical Centre, twenty eight TLDs were exposed and the average skin dose measured was $0.152 \pm 0.01\text{mGy}$. For Bishop Murray Hospital, nine measurements were carried out and the average skin dose measured was $4.207 \pm 0.5\text{mGy}$. The skin dose measured at Federal Medical Centre, Makurdi is found to be within safe radiation dose limit for patients as well as members of the general public. For Bishop Murray Hospitals, the mean dose measured was above the recommended dose by ICRP both for patients and members of the public.

(f) Ajayi and Akinwumiju (2000) estimated ESD to patients in four common diagnostic x-ray examinations (chest, hand and wrist, lumbar spine and skull) at the outpatient department of the University College Hospital Ibadan. Measurement was also based on TLD techniques using lithium fluoride discs and vinten solaro TLD reader. Some spread

was observed in the values of doses received by patients for each of the examinations. It is greatest for the examination of the skull PA and least for the examination of the skull LAT and lumbar spine AP; due mainly to variations in the sizes of the patients examined. For all examinations the values of the mean ESD obtained range from a minimum of 0.310 ± 0.071 mGy to a maximum of 5.66 ± 0.782 mGy for the examination of the hand and wrist PA and lumbar spine LAT, respectively.



CHAPTER THREE

MATERIALS AND METHODS

3.0. Introduction

This chapter outlines the equipment and the methods employed in this study. The chapter consists of three sections. The first section describes the equipment and materials used. The second section outlines the methods employed in the study and the participating facilities. The third section provides the method for radiation risk assessment.

3.1. Equipment

3.1.1. Technical Specification of Digital X-ray Machines

Two x-ray machines were involved in this work. Image of one the X-ray units used for the study and technical specifications of the two digital X-ray machines for the two participating hospitals are presented as Figure 3.1 and Table 3.1 respectively. The two participating hospitals are St. Joseph Orthopedics Hospital (SJOH) and the Eastern Regional Hospital (ERH).



Figure 3. 1. Digital X-ray machine

Table 3. 1. Radiographic technical data for the two X-ray units

Technical Data	Hospital	
	SJOH	ERH
Origin	Japan	Japan
Manufacturer	Shimadzu	Shimadzu
Year manufacture	July, 2012	July, 2012
Model	0.6/1.2P38DE-85	0.6/1.2P38DE-85
Serial Number	CM6F47827024	CM6F47827024
Generator type	3 phase 12 pulse	Constant potential
Beam filtration	1.5 mmAl at 70 kV	1.5 mmAl at 70 kV
Maximum voltage	150 kV	150 kV
Focus	0.6/1.2	0.6/1.2

From Table 3.1, the technical parameters are the same except the generator type. The 3 phase 12 pulse generator for SJOH and the Constant potential generator for ERH.

3.1.2. Simulation of Patient

The Alderson Rando Phantom was used to mimic the characteristics of a living patient in respect of exposure to X-rays. In this study female anthropomorphic phantom was used. It is based on the standard female defined by ICRP (ICRP, 1975) with the phantom's weight of 54 kg and 163 cm in height (Figure 3.2). The phantom contained bone equivalents in the form of human skeleton surrounded by soft tissue equivalent material of 0.985 gcm^{-3} density and 7.3 effective atomic number. The phantom is made up of 35 transverse slices with 2.5 cm thickness each. Every slice has a group of holes filled with pins of tissue equivalent material which can be removed to put dosimeters in the holes. The attenuation property in the diagnostic energy range differs somewhat from human tissue. This difference is considered to result in less than 1% in the calculation of the effective dose (Shrimpton, 1981).

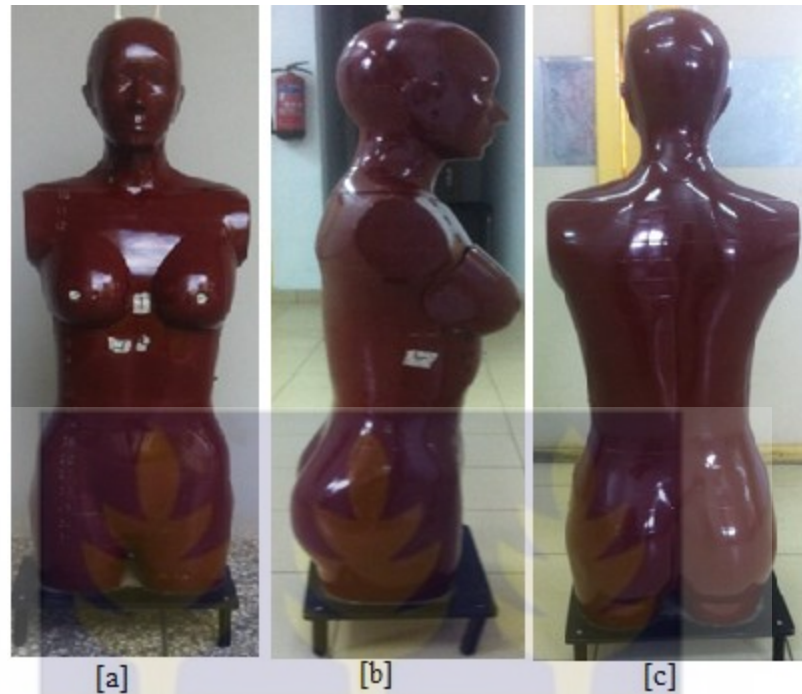


Figure 3. 2. Alderson Rando Phantom [(a) Front view (b) Side view and (c) Back view]

3.1.3. Thermoluminescent Dosimeter (TLD)

The TLDs used were lithium fluoride chips activated with magnesium and titanium to increase sensitivity (Figure 3.3). LiF has been found to be the most popular thermoluminescent material because its deeper traps ensures negligible fading and long term dose storage ability at room temperature though at reduced sensitivity. In addition, its relative low atomic number similar to that of tissue or air gives reasonable constant response to a wide range of photon energies. It has a dimensions of length 2.4 cm, width 0.9 cm and thickness 0.015 cm. LiF has measurement ranges from 10 pGy to 10 Gy.



Figure 3. 3. Lithium fluoride chips

3.1.4. TLD Reader

The TLDs were read using Harshaw Model 6600 Reader of the Radiation Protection Institute, GAEC as shown in Figure 3.4. The reader automatically measures the extremity, environmental, and whole body thermoluminescence dosimetry. It aggregates a medium content (200 TLD Cards or Carrier Cards) transport system with a non-contact heating system for accurate and reproducible measurements with a less operator attention required.

The system consists of two major components: the TLD Reader and the Windows Radiation Evaluation and Management System (WinREMS) software resident on a personal computer (PC), which is connected to the Reader via a serial communications port.

The heating system uses a stream of dry nitrogen at precisely controlled, linearly ramped temperatures to simultaneously heat one or two card positions. Four-chip cards are

read by automatically executing two sequential acquisition-heating cycles without removing and reloading the cards. The hot gas heating and the superior electronic design produce consistent and repeatable glow curves over a wide dynamic range. The non-contact heating extends card life, enabling many more readings and a longer life for each TLD card.

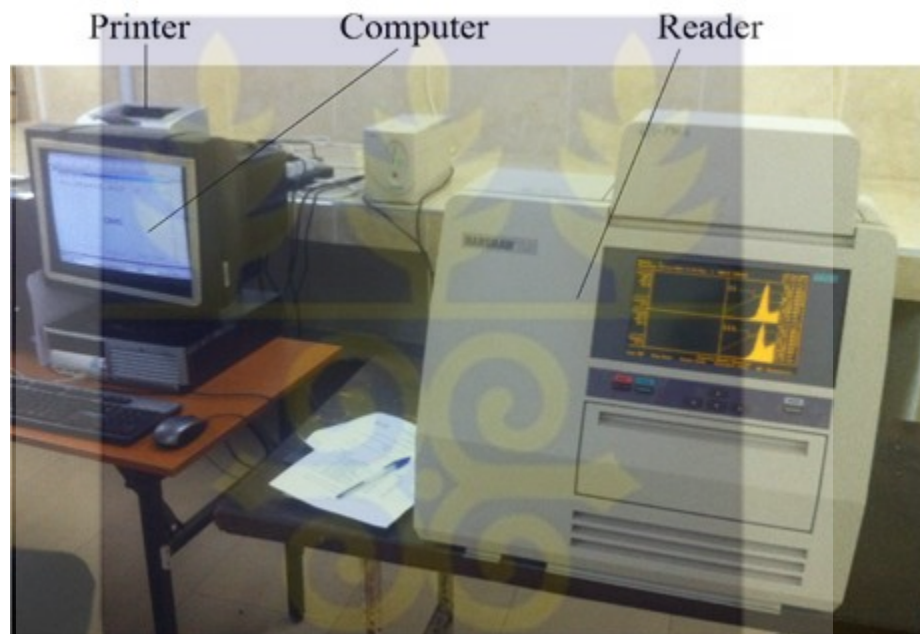


Figure 3. 4. Model 6600 TLD Reader (RPI, GAEC)

3.2. Methods

The study was divided into three sections:

- The first section was dedicated to the assessment of the performance of the two digital X-ray machines.
- The second section was dedicated to the measurement of entrance surface dose using TLDs.

- The third section was dedicated to the assessment of radiation risk to the organs associated with the exposed examinations using PCXMC software version 2.0

3.2.1. Performance assessment (quality control) of X-ray machine

The purpose of any X-ray quality control (QC) is to detect any change in the performance of X-ray machines, which may lead to an unacceptable image quality and high dose to patient and staff (Outif, 2004). This study was performed at the St. Joseph Orthopedics Hospital and the Eastern Regional Hospital. The following QC tests were performed on each X-ray unit in the respective hospitals:

1. Collimation accuracy
2. kVp accuracy and reproducibility
3. Timer accuracy and reproducibility
4. Tube output reproducibility
5. Tube output consistency with mAs (linearity)
6. Filtration (HVL) check

3.2.1.1. Collimation accuracy

In this work the beam alignment was assessed using the beam alignment test tool (Figure 3.5a) and the collimator test tool (Figure 3.5b) measured at 100 cm from the tube focus with the beam alignment test tool on top of the collimator test tool. The beam alignment test tool was centered to the collimator test tool and both the alignment and collimator test tools were put on the X-ray table centered to the image receptor. The X-ray

film (with cassette) was placed in the X-ray Bucky, and the X-ray field was centered to the film and the test tools using the light field (Figure 3.6). The cassette was then exposed and the film read by the reader to visualize the image produced.

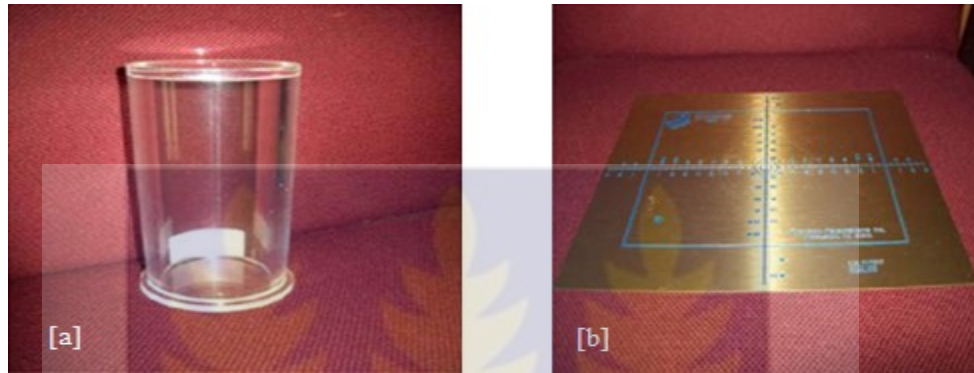


Figure 3. 5. [a] Beam alignment tool [b] Collimator tool

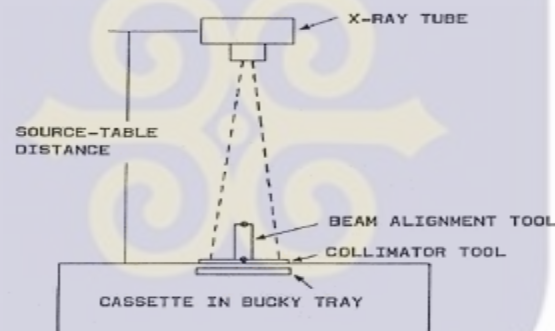


Figure 3. 6. Schematic diagram of experimental setup collimation test

For the machine to pass this test, X-ray field must fall within the image of the rectangular frame for a good alignment. Two steel balls in the beam alignment tool must fall within the first circle for 1.5° deviation or the second circle for 3° deviation. (Outif, 2004).

3.2.1.2. kVp accuracy test and reproducibility

Firstly, the RMI Multi-function meter (Figure 3.7) was set at a distance of 100 cm from the X-ray tube focus and was centered using laser as shown in Figure 3.7. Then 20 mAs was set on the machine control panel. The kVp was then measured from 60-120 kVp in increment of 10. At every set kVp on the control panel, the measured kVp was recorded.



Figure 3. 7. RMI Multi-function meter

To assess kVp accuracy, the test was first performed with constant mAs and variable kVp. Both the dialled kVp (DkVp) and the measured kVp (MkVp) were noted and the percentage difference between the DkVp and the MkVp, were then calculated for each DkVp using the following equation:

$$\%dif(kVp) = \frac{DkVp - MkVp}{MkVp} \times 100 \quad 3.0$$

For the machine to pass this test, the percentage difference between the DkVp and MkVp should be within $\pm 6\%$ (Outif, 2004).

To assess kVp reproducibility, the test was performed with constant kVp and variable mAs. The DkVp and MkVp were noted and the MkVp coefficient of variance (CV) was then calculated using the following equation:

$$CV = \frac{S}{m} \quad 3.1$$

Where S is the estimated standard deviation of the different MkVp and m is the mean of the MkVp. For the machine to pass this test, the coefficient of variance (CV) of the MkVp should be ≤ 0.05 (Frigren, 1990).

3.2.1.3. Timer accuracy and reproducibility

Exposure time directly affects the quantity of radiation emitted from an X-ray tube, therefore, a precise exposure timer is vital for properly exposed diagnostic examination and minimum patient dose. Any appreciable variation from the desired exposure time may lead to poor image quality and/or an increased patient and staff radiation dose.

To assess timer accuracy, the RMI meter was placed under the X-ray tube in the same arrangement as that used for kVp accuracy and reproducibility (see section 3.2.1.2). Several exposures with constant kVp and mA and with variable exposure time that cover the whole possible exposure time range were then performed. The dialed exposure time (DEXT) and the measured exposure time (MEXT) were noted and the percentage difference between DEXT and MEXT was then calculated using the following equation:

$$\%dif (EXT) = \frac{DEXT - MEXT}{MEXT} \times 100 \quad 3.2$$

For the machine to pass this test, the percentage difference between DEXT and MEXT should be within $\pm 5\%$ (for exposure times greater than 10 ms) and $\pm 10\%$ (for exposure times less than 10 ms) (Outif, 2004).

To assess timer reproducibility, the multimeter was placed under the X-ray tube in the same arrangement as that used in section (3.2.1.2). Several exposures with constant exposure time and appropriate kVp and mAs were then performed. The coefficient of variance (CV) of the exposure time was then calculated using the following equation:

$$CV = \frac{S}{m} \quad 3.3$$

Where S is the estimated standard deviation of the different measured MEXT and m is the mean of MEXT. For the machine to pass this test, the MEXT CV of the exposure time must be less than 5% (Outif, 2004).

3.2.1.4. Tube output reproducibility

Assessment of the tube output is considered as one of the most important QC tests. Consistency of the tube output for a given exposure factor would help to provide reproducible image quality. Any X-ray machine should always produce the same output each time the same exposure factors are used.

This test was also performed using Rad-Check Plus meter. The Rad-Check Plus meter was placed under the X-ray tube in the same arrangement as that used in section 3.2.1.2. Several exposures with constant kVp and mAs were taken, and the output for each exposure was noted. The coefficient of variance (CV) of output was then calculated using the following formula:

$$CV = \frac{S}{m} \quad 3.4$$

Where S is the calculated standard deviation of the tube output, and m is the mean of the tube output. For the machine to pass this test, the CV of the tube output must be less than 5% (Outif, 2004)

3.2.1.5. Tube output consistency with mAs (linearity)

This test was performed with Rad-Check Plus meter (Figure 3.8) and arrangement was same as that used in section 3.2.1.2. Several exposures with variable mAs and constant kVp were done. The output of each X-ray machine for each exposure was recorded. The relationship between the tube current and tube output were plotted and the relationship between the tube current and output per unit mAs were also plotted. The linearity variance (LV) was calculated using the following equation:

$$LV = \left[\frac{(mR/mAs)_{max} - (mR/mAs)_{min}}{(mR/mAs)_{avg}} \right] \div 2 \quad 3.5$$

Where $(mR/mAs)_{max}$ is the maximum reading of the tube output per mAs, $(Output/mAs)_{min}$ is the minimum reading of the tube output per mAs and $(Output/mAs)_{avg}$ is the average of the tube output per mAs. For the machine to pass this test, the plot of tube current against tube output must be a straight line, and the plot of the tube current against tube output per unit mAs must be a horizontal straight line. And the linearity variance (LV) must be less than 20% (Cranley, 1995). A higher linearity variance indicates problems with the X-ray generator, such as the milliamperage selector, timer circuitry or rectifier failure.



Figure 3. 8. Rad-Check Plus meter

3.2.1.6. Filtration (Half Value Layer) check

Filtration is necessary to eliminate low-energy photons from an X-ray beam. Patient's skin dose can increase as much as 90% if the low energy photons are not removed (Outif, 2004). Half Value Layer deteriorate when X-ray tube ages due to deposition of the target material and roughening of the target.

This test was performed using the following devices: Aluminum (Al) attenuator set, Rad-Check Plus meter and lead vinyl. The meter was placed at 100 cm from the tube focus on the lead vinyl to standardize backscatter. The kVp was set at 80 and fixed value of 20 mAs. The X-ray beam was collimated to the size of the meter. Three exposures were taken and the resulting doses were recorded. Another set of exposures and dose measurements were taken after placing a 1.0 mm thick Al attenuator on the collimated area of the Rad Check Plus meter. Further exposures and dosage measurements were taken after adding

varying thicknesses of Al attenuators until the dose reduce to half of its original value (without filter). The relationship between total Al thickness, and the measured output was plotted. From the figure, the thickness required to reduce the exposure to half of its original value (without filter) was determined.

3.2.2. Measurement of Entrance Surface Dose with TLDs

The St. Joseph Orthopedics Hospital and the Eastern Regional Hospital were chosen for the study because they are the two largest hospitals in the Eastern Region of Ghana in terms of workload and size. Questionnaires were distributed to radiographers in charge of the diagnostic facilities to provide information with regard to their radiography units. Information provided include origin, manufacturer of equipment, year of manufacture, model, serial number, generator type, beam filtration, maximum kVp and focus size.

Measurement of entrance surface dose was made with TLDs chip stick to the skin surface of the phantom. The diagnostic X-ray examinations performed on the phantom were classified into four groups according to the section of the body examined namely: skull, chest, pelvis and lumbar spine. The X-ray projections include anterior-posterior (AP), posterior-anterior (PA) and lateral view.

3.2.2.1. Data Collection with TLDs

After the phantom was positioned for a particular X-ray examination, the single chip TLDs stuck to a cello tape was placed at the central point of the beam axis on the part

of the phantom under projection. The radiographer then selects the appropriate exposure factors and the exposure was made. The TLDs were placed in their holders to prevent contamination of dirt and grease from handling, which affect its luminescence property. The acceptability of these diagnostic images was purely subjective and was assessed by the radiographers which can possibly introduce bias. The exposed TLDs were subsequently sent to Ghana Atomic Energy Commission for reading. Figure 3.9 show how the phantom was positioned for the various examinations.

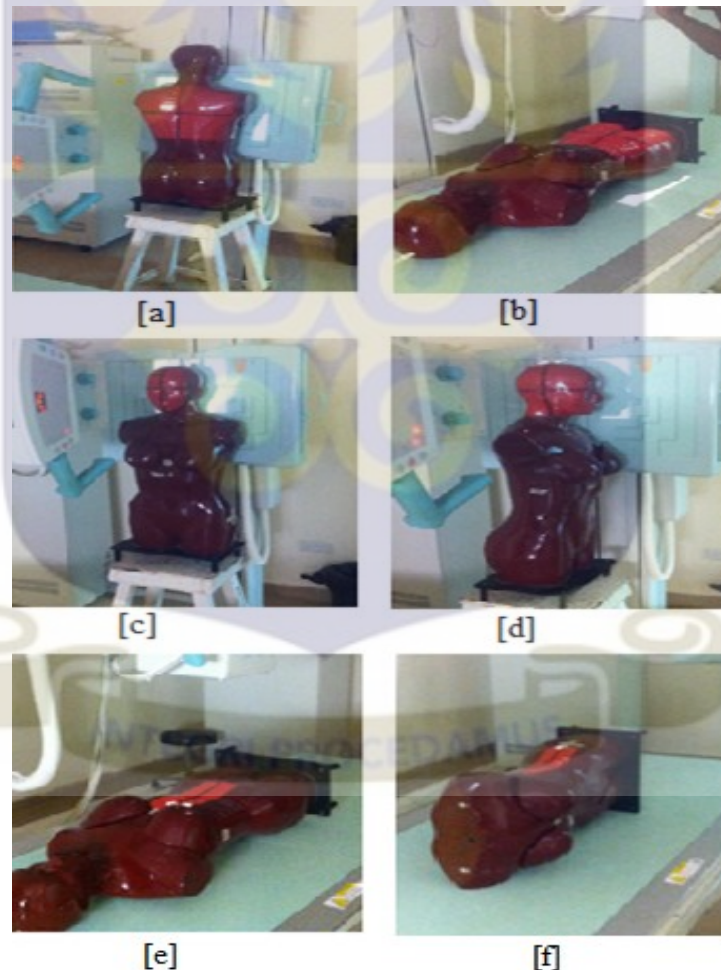


Figure 3. 9. Exposures of [a] Chest PA [b] Pelvis AP [c] Skull AP [d] Skull Lateral [e] Lumbar spine AP and [f] Lumbar spine Lateral

3.2.2.3. Radiation Risk Assessment

The assessment of radiation risk is estimated by the PCXMC software version 2.0. The PCXMC is a Monte Carlo program for accounting for patients' organ doses and effective doses in medical X-ray examinations. The PCXMC uses linear no-threshold model to estimate the long-term biological damage caused by ionizing radiation. The program calculates the effective dose with both the present tissue weighting factors of ICRP Publication 103 (ICRP, 2007) and the old tissue weighting factors of ICRP Publication 60 (ICRP, 1991). The anatomical data are based on the mathematical phantom models (Cristy et al., 1987). The PCXMC software consist of six main interfaces. To assess radiation risk, four steps were involved in the process; the first step was to input the weight and height parameters in the examination data interface. Phantom weight and height were entered to develop a mathematical phantom to represent the patient. The focus film distance and the image size at focus film distance were entered to obtain the focus skin distance and the image size at focus skin distance. The examination projection was also entered to this interface. The developed examination data was saved for simulation. In the simulation stage (second step), the saved examination data is called and simulated. This takes a few seconds.

After simulation, the third step was to compute the organ dose and the effective dose. This was done by using the Compute dose button. To compute the doses, the kVp and the tube filtration were entered to generate the X-ray spectrum for the examination. After generating the X-ray spectrum, the entrance surface dose was entered and by clicking the Ok button, the doses to the organs (mGy) and the effective dose (mSv) were calculated

and displayed. At the final stage, the data from the computed doses were called back before the button was pressed to calculate the radiation risk.

The Monte Carlo calculation of photon transport is based on stochastic mathematical simulation of interactions between photons and matter. Calculated organ doses are used for the assessment of the risk of exposure induced cancer. The risk estimates are based on the combined absolute and relative risk models of Biological Effects of Ionizing Radiations VII committee (BEIR, 2006). Age-dependent mortality rates are used for subsequent assessment of lifetime cancer risk. The excess risk values are the basis of the lifetime risk estimates. The lifetime risks can be assessed with various quantities. PCXMC uses three different quantities:

- Risk of exposure-induced death (REID). The concept of REID originates from cohort analysis techniques: death rates in the exposed and in the unexposed cohorts are compared. A null hypothesis corresponds to a statistically negligible difference between the two groups. A positive REID value indicates excess deaths in the exposed cohort.
- Loss of life expectancy (LLE) is the difference between the expectation of life for a person exposed at age e and of an unexposed person who was alive at that age.
- Loss of life expectancy per radiation induced fatal cancer (LLE/REID) describes the average length of life lost per excess cancer death.

CHAPTER FOUR

RESULT AND DISCUSSION

4.0. Introduction

This chapter presents the results of the study and discusses the results from quality control, patient's dose and exposure technique factors collected at the X-ray units from the two participating facilities. Comparison of dose data with DRLs and the assessment of radiation risk with PCXMC software are also presented.

4.1. Results of the performance assessment (QC) of X-ray machines

The assessment of the physical operations of the X-ray equipment is one of the most important aspects of optimization of patient's dose and image quality. These assessments were conducted on two Shimadzu digital X-ray machines. The results of each X-ray machines are discussed separately.

4.1.1. Results and discussions of QC for St. Joseph Orthopedics Hospital (SJOH)

4.1.1.1. Collimation accuracy

This assessment was conducted at 100 cm FFD, 80 kVp, 10 mAs and field sizes that coincided with the rectangle outline on the collimator tool. The figure 4.1 shows the image of the beam collimation test.

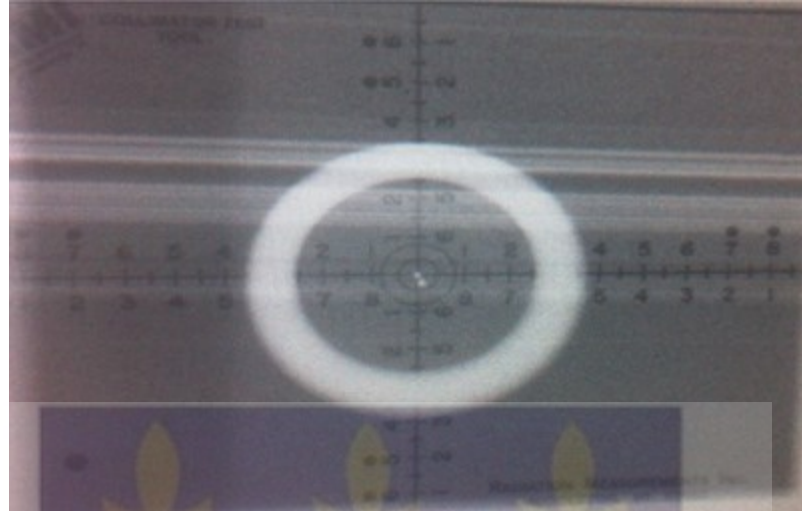


Figure 4. 1. Radiograph of the beam collimation tool

From Figure 4.1, the X-ray field falls within the image of the rectangular frame. The images of the two steel balls fall in the center of the first circle on the test tool. This indicates a good alignment by a deviation which is less than 1.5° . The X-ray unit passed the collimation test.

4.1.1.2. kVp accuracy test

This test was conducted at 100 cm FFD, 10 mAs and $6 \times 15 \text{ cm}^2$ field sizes. The kVp accuracy was performed from 60 to 90 kVp. Table 4.1 summarizes the result of this test.

Table 4. 1. Results of the kVp accuracy for SJOH

DkVp	MkVp			Avg MkVp	Percentage Difference	Remarks
	1	2	3			
60	58.9	58.9	58.7	58.83	1.983	Pass
70	69.3	69.6	69.5	69.47	0.768	Pass
80	80.3	80.0	80.9	80.40	-0.498	Pass
90	90.3	90.1	90.2	90.20	-0.222	Pass

From Table 4.1, the calculated minimum percentage difference was – 0.222 at 90 kVp and the maximum percentage difference was 1.983 at 60 kVp. The X-ray unit is within the acceptable deviation of $\pm 6\%$. The X-ray unit passed the kVp accuracy test.

4.1.1.3. kVp reproducibility

This test was conducted at 100 cm FFD, 90 kVp and 6 x 15 cm² field sizes. Table 4.2 summarizes the result of this test. The test was performed at different mAs settings from the range of 3.5 mAs to 12.5 mAs.

Table 4. 2. Results of kVp reproducibility for SJOH

DmAs	MkVp			Avg MkVp	STDEV	CV	Remarks
	1	2	3				
3.5	58.9	58.5	58.7	58.70	0.20	0.00	Pass
6.5	69.3	69.5	69.5	69.43	0.12	0.00	Pass
9.0	80.3	80.0	80.9	80.40	0.46	0.01	Pass
12.5	90.3	90.1	90.2	90.20	0.10	0.00	Pass

From Table 4.2, the calculated coefficient of variance (CV) of the kVp reproducibility was equal to 0.00. The X-ray unit is within the acceptable limit (< 0.05) and has passed the test.

4.1.1.4. Timer accuracy

The procedure used was the same as in section 4.1.1.2 to perform the X-ray tube potential accuracy test. Table 4.3 summarizes the outcome of this test.

Table 4. 3. Results of timer accuracy for SJOH

DEXT	MEXT	Percentage Difference (EXT)	Remarks
20	20.1	-0.50	Pass
20	20.1	-0.50	Pass
21	21.1	-0.47	Pass
21	21.1	-0.94	Pass
22	22.1	-0.45	Pass

From Table 4.3, the calculated minimum percentage difference exposure time was -0.45 and the maximum percentage difference exposure time was -0.94. The equipment passed the test, since the values for all percentage differences of the exposure time are less than $\pm 5\%$.

4.1.1.5. Timer reproducibility

This test was conducted at 100 cm FFD, 10 mAs and 6 x 15 cm² field size. Table 4.4 summarizes the result of this test.

Table 4. 4. Results of the exposure time reproducibility for SJOH

DEXT	MEXT	STDEV (MEXT)	AVERAGE MEXT	CV
20	20.1	0.844	20.92	0.04
20	20.1			
21	21.1			
21	21.2			
22	22.1			

From Table 4.4, the calculated coefficient of variance (CV) was 0.04, and this was within the acceptable limit of 0.05, hence the test was passed accordingly.

4.1.1.6. Tube output reproducibility

This test was conducted at 100 cm FFD, 80 kVp, 12.5 mAs and 12 x 12 cm² field size. Table 4.5 summarizes the result of the tube output reproducibility.

Table 4. 5. Results of the tube output reproducibility for SJOH

kVp	mAs	Output (mR)			STDEV	AVERAGE	CV (%)	Remarks
60	6.3	0.2	0.2	0.2	0.0058	0.2	0.026	Pass
60	8.0	0.3	0.3	0.3	0.0000	0.3	0.000	Pass
60	12.5	0.4	0.4	0.4	0.0000	0.4	0.000	Pass
70	6.3	0.3	0.3	0.3	0.0058	0.3	0.019	Pass
70	8.0	0.4	0.4	0.4	0.0058	0.4	0.015	Pass
70	12.5	0.6	0.6	0.6	0.0058	0.6	0.009	Pass
80	6.3	0.4	0.4	0.4	0.0058	0.4	0.015	Pass
80	8.0	0.5	0.5	0.5	0.0000	0.5	0.000	Pass
80	12.5	0.8	0.8	0.8	0.0100	0.8	0.013	Pass

From Table 4.5, the calculated coefficient of variances (CV) are all within the acceptable limit ($\pm 5\%$).

4.1.1.7. Tube output consistency with mAs (linearity)

This test was conducted at the 100 cm FFD, 60 kVp, 6 x 15 cm² field sizes and variable mAs (6.3 to 12.5 mAs) setting. Study was repeated at 70 kVp and 80 kVp. Table 4.6 summarizes the result of this test.

Table 4. 6. Results of tube output consistency with mAs (linearity) for SJOH

kVp	mAs	Output (mR)			Average (mR)	mR/mAs	LV (%)
60	6.30	0.23	0.22	0.22	0.22	0.035	0.0064
	8.00	0.28	0.28	0.28	0.28	0.035	
	12.50	0.44	0.44	0.44	0.44	0.035	
70	6.30	0.31	0.30	0.31	0.31	0.049	0.0102
	8.00	0.39	0.39	0.38	0.39	0.048	
	12.50	0.62	0.62	0.61	0.62	0.049	
80	6.30	0.39	0.40	0.40	0.40	0.063	0.0082
	8.00	0.51	0.51	0.51	0.51	0.064	
	12.50	0.80	0.79	0.81	0.80	0.064	

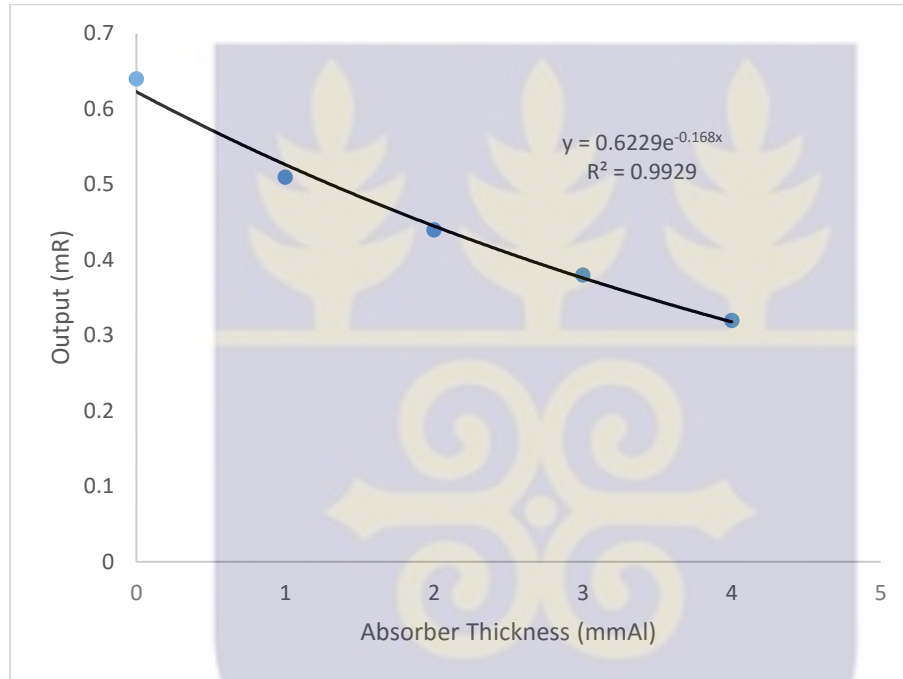
From Table 4.6, the linearity variances (LV) for the machine were 0.0064%, 0.0102% and 0.0082% for 60 kVp, 70 kVp and 80 kVps respectively. The results test were within acceptable limit of 20%.

4.1.1.8. Filtration (HVL) check

This test was conducted at 100 cm FFD, 80 kVp, 12.5 mAs and 12 x 12 cm² field size. The test was performed at a variable thickness of aluminum filter from 0 to 4 mmAl. Table 4.7 summarizes the result of this test.

Table 4. 7. Results of filtration (HVL) check for St. Joseph Orthopedics Hospital

Absorber thickness (mmAl)	Output
0	0.64
1	0.51
2	0.44
3	0.38
4	0.32

**Figure 4. 2. Half Value Layer (HVL) graph at 80 kVp for SJOH**

From Figure 4.2, the determined HVL was 3.97 mmAl. The value is within the acceptable range of ≥ 2.10 mmAl for 80 kVp.

4.2.2. Results and discussions of QC for Eastern Regional Hospital (ERH)

4.2.2.1. Collimation accuracy

This assessment was conducted at 100 cm FFD, 80 kVp, 10 mAs and field sizes that coincided with the rectangle outline on the collimator tool. The Figure 4.3 shows the image of the beam collimation test.



Figure 4. 3: Radiograph of the beam collimation tool

From Figure 4.3, the X-ray field falls within the image of the rectangular frame. The images of the two steel balls fall in the center of the first circle on the test tool. This implies a good alignment by a deviation which is less than 1.5° and that make the X-ray unit to pass the collimation test.

4.2.2.2. kVp accuracy

This test was conducted at 100 cm FFD, 10 mAs and 6 x 15 cm² field sizes. The kVp accuracy was performed from 60 to 90 kVp. Table 4.8 summarizes the result of this test.

Table 4. 8. Results of kVp accuracy for ERH

DkVp	MkVp			Avg MkVp	Percentage Difference	Remarks
	1	2	3			
60	59.9	60.0	60.1	60.00	0.000	Pass
70	70.0	70.5	70.8	70.43	-0.615	Pass
80	81.2	81.2	81.0	81.13	-1.397	Pass
90	91.5	91.1	92.1	91.57	-1.711	Pass

From Table 4.8, the calculated minimum percentage difference was -0.000 at 60kVp and the maximum percentage difference was -1.711 at 90 kVp. The X-ray unit is within the acceptable deviation of $\pm 6\%$. The equipment therefore passed the kVp accuracy test.

4.2.2.3. kVp reproducibility

This test was conducted at 100 cm FFD, 90 kVp and 6 x 15 cm² field sizes. Table 4.9 summarizes the result of this test. The test was performed at different mAs settings from the range of 3.5 mAs to 12.5 mAs.

Table 4. 9. Results of the X-ray tube potential reproducibility for ERH

DmAs	MkVp			Avg MkVp	STDEV	CV	Remarks
	1	2	3				
3.5	59.9	60.0	60.1	60.00	0.10	0.00	Pass
6.5	70.0	70.5	70.8	70.43	0.40	0.01	Pass
9.0	81.2	81.2	81.0	81.13	0.12	0.00	Pass
12.5	91.5	91.1	92.1	91.57	0.50	0.01	Pass

From Table 4.9, the calculated coefficient of variance (CV) of the kVp reproducibility was equal to 0.00. The X-ray unit is within the acceptable limit (< 0.05) and has passed the test.

4.2.2.4. Timer accuracy

The procedure used was the same as in section 4.1.2.2 to perform the kVp accuracy test. Table 4.10 summarizes the result of this test.

Table 4. 10. Results of timer accuracy for ERH

DEXT	MEXT	Percentage Difference (EXT)	Remarks
20	20.0	0.000	Pass
20	20.1	-0.498	Pass
20	20.1	-0.498	Pass
20	20.1	-0.498	Pass
20	20.1	-0.498	Pass

From Table 4.10, the calculated minimum percentage difference in exposure time was -0.000 and the maximum percentage difference exposure time was -0.498. The machine passed the test, since the values for all percentage differences in exposure time were less than $\pm 5\%$.

4.2.2.5. Timer reproducibility

This test was conducted at 100 cm FFD, 10 mAs and 6 x 15 cm² field size. Table 4.11 summarizes the result of this test.

Table 4. 11. Results of the exposure time reproducibility for ERH

DEXT	MEXT	STDEV (MEXT)	AVERAGE MEXT	CV
20	20.0	0.045	20.08	0.00
20	20.1			
20	20.1			
20	20.1			
20	20.1			

From the Table 4.11, the calculated coefficient of variance (CV) was equal 0.00, and this was within the acceptable limit of 0.05 and pass the test accordingly.

4.2.2.6. Tube output reproducibility

This test was conducted at 100 cm FFD, 80 kVp, 12.5 mAs and 12 x 12 cm² field size. Table 4.12 summarizes the result of the tube output reproducibility.

Table 4. 12. Results of the tube output reproducibility for ERH

kVp	mAs	Output (mR)			STDEV	AVERAGE	CV(%)	Remarks
60	6.3	0.08	0.08	0.08	0.00	0.08	0.00	Pass
60	8.0	0.12	0.11	0.11	0.01	0.11	0.05	Pass
60	12.5	0.16	0.16	0.16	0.00	0.16	0.00	Pass
70	6.3	0.11	0.11	0.11	0.00	0.11	0.00	Pass
70	8.0	0.16	0.16	0.16	0.00	0.16	0.00	Pass
70	12.5	0.22	0.22	0.21	0.01	0.23	0.03	Pass
80	6.3	0.14	0.14	0.14	0.00	0.14	0.00	Pass
80	8.0	0.20	0.20	0.20	0.00	0.20	0.00	Pass
80	12.5	0.28	0.28	0.29	0.01	0.28	0.02	Pass

From Table 4.12, the calculated coefficient of variance (CV) was equal to 0.02%, and this value was within the acceptable limit ($\pm 5\%$).

4.2.2.7. Tube output consistency with mAs (linearity)

This test was conducted at the 100 cm FFD, 60 kVp, 6 x 15 cm² field sizes and variable mAs (6.3 to 12.5 mAs) setting. The study was repeated at 70 kVp and 80 kVp. Table 4.13 summarizes the result of this test.

Table 4. 13. Results of tube output consistency with mAs (linearity) for ERH

kVp	mAs	Output (mR)			Average (mR)	mR/mAs	LV (%)
60	6.30	0.08	0.08	0.08	0.08	0.013	0.055
	8.00	0.12	0.11	0.11	0.11	0.014	
	12.50	0.16	0.16	0.16	0.16	0.013	
70	6.30	0.11	0.11	0.11	0.11	0.018	0.071
	8.00	0.16	0.16	0.16	0.16	0.020	
	12.50	0.22	0.22	0.21	0.22	0.017	
80	6.30	0.14	0.14	0.14	0.14	0.022	0.059
	8.00	0.20	0.20	0.20	0.20	0.025	
	12.50	0.28	0.28	0.29	0.28	0.023	

From Table 4.13, the linearity variances (LV) for the machine were 0.055%, 0.071% and 0.059% for 60 kVp, 70 kVp and 80 kVps respectively. The test was within acceptable limit of 20%.

4.2.2.8. Filtration (HVL) check

This test was conducted at 100 cm FFD, 80 kVp, 12.5 mAs and 12 x 12 cm² field size. The test was performed at a variable thickness of aluminum filter from 0 to 4 mmAl. Table 4.14 summarizes the result of this test.

Table 4. 14. Results of filtration (HVL) check for ERH

Absorber thickness (mmAl)	Output
0	0.54
1	0.41
2	0.33
3	0.28
4	0.20

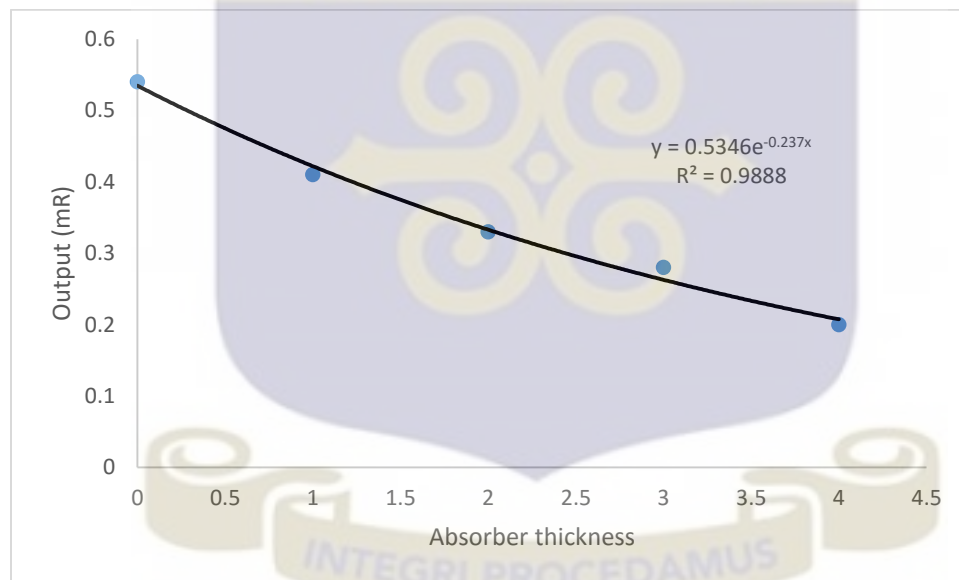


Figure 4. 4. Half Value Layer (HVL) graph for ERH

From Figure 4.4, the determined HVL was 2.8 mmAl. The value is within the acceptable range of ≥ 2.10 mmAl for 80 kVp.

4.3. Analysis of Entrance Surface Dose measurement

4.3.1. Statistics of examinations and phantom base data

Dose measurements were calculated on 384 exposures on the anthropomorphic phantom of which 261 exposures (68%) were for ERH and 123 exposures (32%) were for SJOH. Distribution of the total exposures for the two participating hospitals during the study period is presented in Figure 4.5 below.

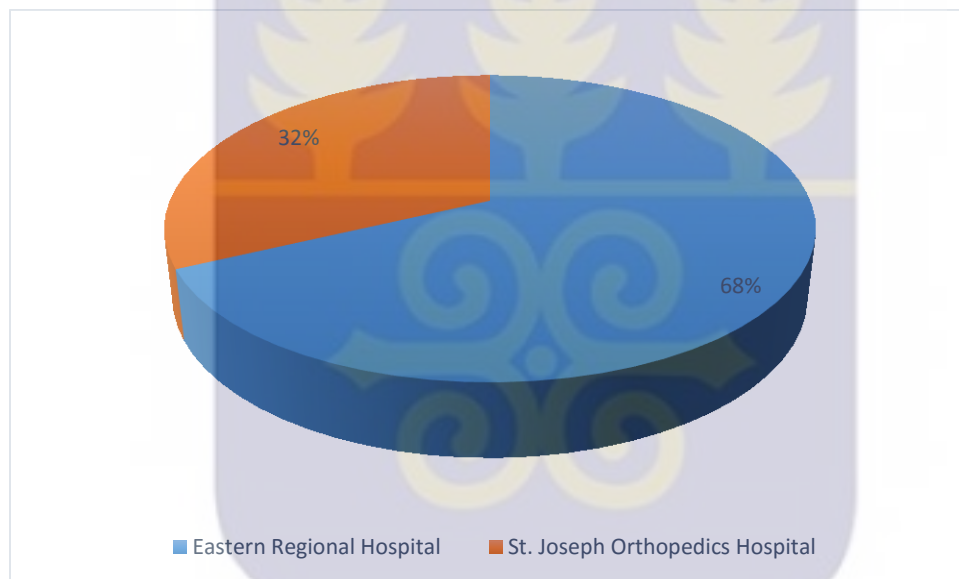


Figure 4. 5. Distribution of the total exposures for the two participating hospitals

From the Figure 4.5, ERH has the highest number of exposures as compare to SJOH where general radiographic examinations are done. SJOH is a specialized hospital for trauma and orthopedics examinations. This hospital conducts lumbar spine, hip joint and some chest X-rays examinations. ERH is opened to all radiographic examinations and for that matter, much of my exposures were concentrated there which accounted for the 68% as compared to 32% of the St. Joseph hospital which less exposures were taken due to its

specialty in disorders or deformities of the spine, joints and bones. Also, there was less pressure in the ERH which I had much time to take more exposures as compared to SJOH where the X-ray machine was always on the used.

4.3.2. Phantom demographic and examination data

The phantom for the study is an adult female anthropomorphic phantom of 1.62 m height and 54 kg weight. The average age of phantom considered for the study was 35 years. The average age was within the age range in Malaysia (14 – 92 years) and United Kingdom (16 – 99 years) (Brennan et al., 2004). The average thickness and the body mass index (BMI) of phantom selected for the study are 20 cm (16 – 24 cm) and 20.6 kg/m². The World Health Organization regards a BMI of a normal (healthy weight) person to be in the range of 18.5 - 24.99 kg/m² (ICRP, 2012). This also shows that the average BMI of the phantom selected for the study was within WHO's normal BMI range. The radiographic examination areas of the phantom anatomical thickness are 18 cm, 16 cm, 24 cm, 21 cm, 16 cm and 18 cm for chest (PA), lumbar spine (AP), lumbar spine (lateral), pelvis (AP), skull (lateral) and skull (AP) respectively.

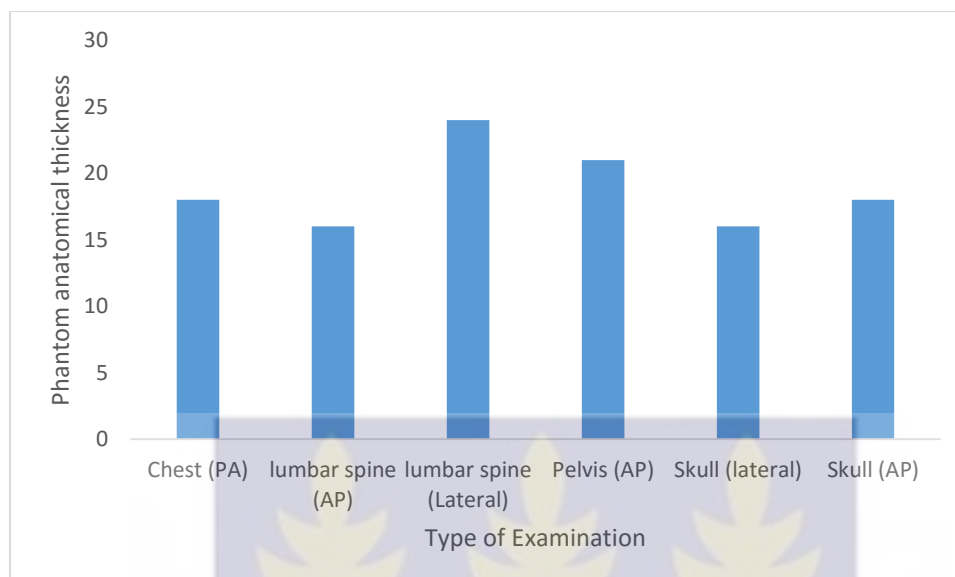


Figure 4. 6. Phantom anatomical thickness for the selected radiographic examinations of the study

From Figure 4.6, lumbar spine (lateral) was the highest thickness followed by pelvis (AP). The chest (PA) and Skull (AP) have the same thickness and lumbar spine (AP) and skull (lateral) also have the same thickness. Their thicknesses varies due to the anatomical nature of the phantom. The lumbar spine (lateral) and pelvis (AP) were given higher exposure of radiation as compared to chest (PA), skull (AP), lumbar spine (AP) and skull (lateral). This was due to the anatomical thickness of the examination area.

Diagnostic procedures are the most common application of radiations in medicine. In Ghana, for that matter in the Eastern Region widespread use of X-rays in digital radiography accounts for largest exposure of the population to radiations (ICRP, 1996). Distribution of the selected examinations in the participating hospitals during the study period is presented in Figure 4.7 below.

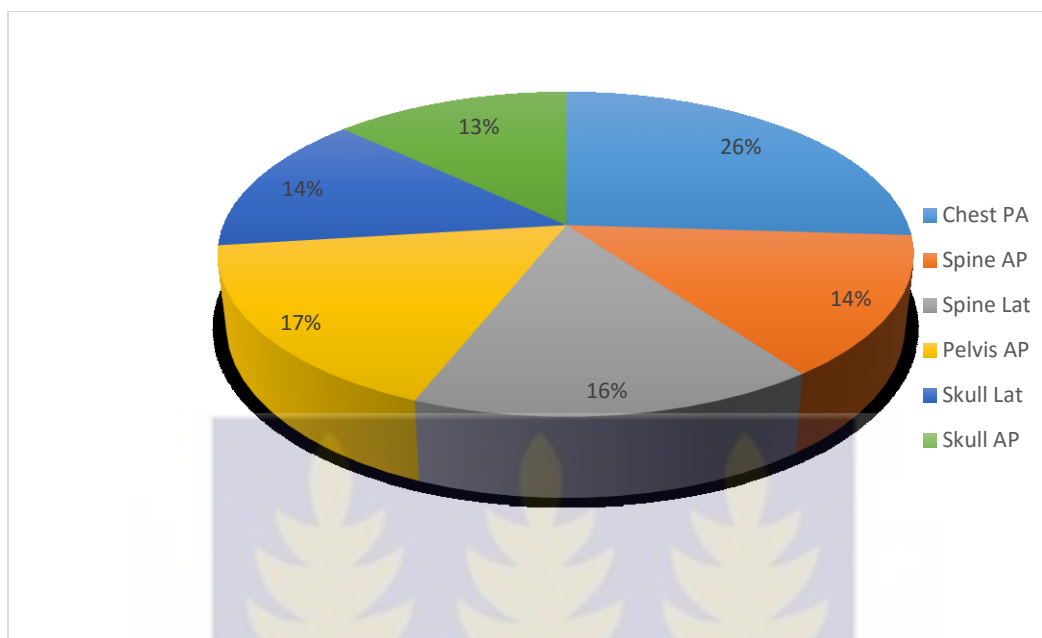


Figure 4. 7. Distribution of the selected examination for the two participating hospitals

Figure 4.7 contains the chest PA, spine AP, spine lateral, pelvis AP, skull lateral and skull AP examinations. About 26% of the examinations were chest (PA) X-rays. Pelvic (AP) and lumbar spine (lateral) examinations accounts for about 17% and 16% of the total exposure of the phantom respectively. Skull (lateral) and lumbar spine (AP) examinations accounts for 14% each. Least of the examinations was skull (AP) with 13%. Figure 4.7 shows that chest radiography remains a very common and most frequently performed X-ray examination in diagnostic radiology. It contributes to about 26% of the exposures made from the phantom in SJOH and ERH.

4.3.3. Exposure parameters and radiographic techniques

The summary of the exposure factors (kVp and mAs) with the mean, range (in parenthesis) selected for various examinations at the two participating hospitals are presented in Table 4.15. The most common values of the tube voltage (kVp) and the tube loading (mAs) selected are presented to the right of the range. The exposure techniques (FFD in cm) are also presented in Table 4.15.

Table 4. 15. Exposure parameters for selected X-ray examination, with mean values and range (in parentheses)

Projection	Tube voltage		mAs		FFD/cm	
	SJOH	ERH	SJOH	ERH	SJOH	ERH
Chest (PA)	74 (65-84)	91 (80-102)	2.5 (1.8-3.2)	2.9 (1.8-4)	180	150
Lumbar spine (AP)	73 (70-76)	88 (80-96)	6.3 (4.5-8.0)	31 (22-40)	100	100
Lumbar spine (Lateral)	84 (80-88)	88 (80-96)	8.0 (6.3-10)	31 (22-40)	100	100
Pelvis (AP)	64 (60-68)	94 (90-98)	4.5 (4.5-5.0)	36 (32-40)	100	100
Skull (Lateral)	68 (66-70)	70 (70-70)	6 (4-8)	13.5 (12.5-14)	100	100
Skull (AP)	75 (70-80)	70 (70-70)	6.1 (5-7.1)	13.5 (12.5-14)	100	100

From Table 4.15, the range of tube voltage (60-120 kVp) mostly selected for all the radiographic examinations were within the range of tube potential selected in the UK (50-150 kVp). In the case of the tube loading (mAs), the range (1.8-45 mAs) was partly outside and partly within the UK survey (5-485 mAs). The highest range of kVp happened in ERH

for chest PA of kVp range value of 80-102 kVp and that of the highest range of mAs happened in SJOH for pelvis AP of mAs range value of 32-40 mAs. This was due to the generator type of the X-ray machine, phantom anatomical thickness and also the quality of the image. The European Commission in its document, European Guidelines on Quality Criteria for Diagnostic Radiographic Images (CEC, 1996) recommends the usage of high kV of 125 kVp for chest radiograph. From Table 4.15, all the facilities fell short to this recommendation. The range of the tube potential used for chest radiography is (60-120 kVp).

From Table 4.15, the range of FFD (in centimeters) used was (100-180 cm). This was within the optimum values (80-210 cm) required. There was a constant FFD of 150 cm for the chest (AP) examination and 100 cm for other examinations performed at ERH. This was due to a constant distance between the tube housing and the cassette holder. The other facility used a constant FFD of 180 cm for chest (PA) examinations and 100 cm for other examinations.

4.3.4. Assessment of entrance surface dose in the two hospitals

The mean ESD (mGy) was computed for chest (PA), lumbar spine (AP/Lateral), pelvis (AP) and skull (Lateral/AP) examinations for the two participating hospitals.

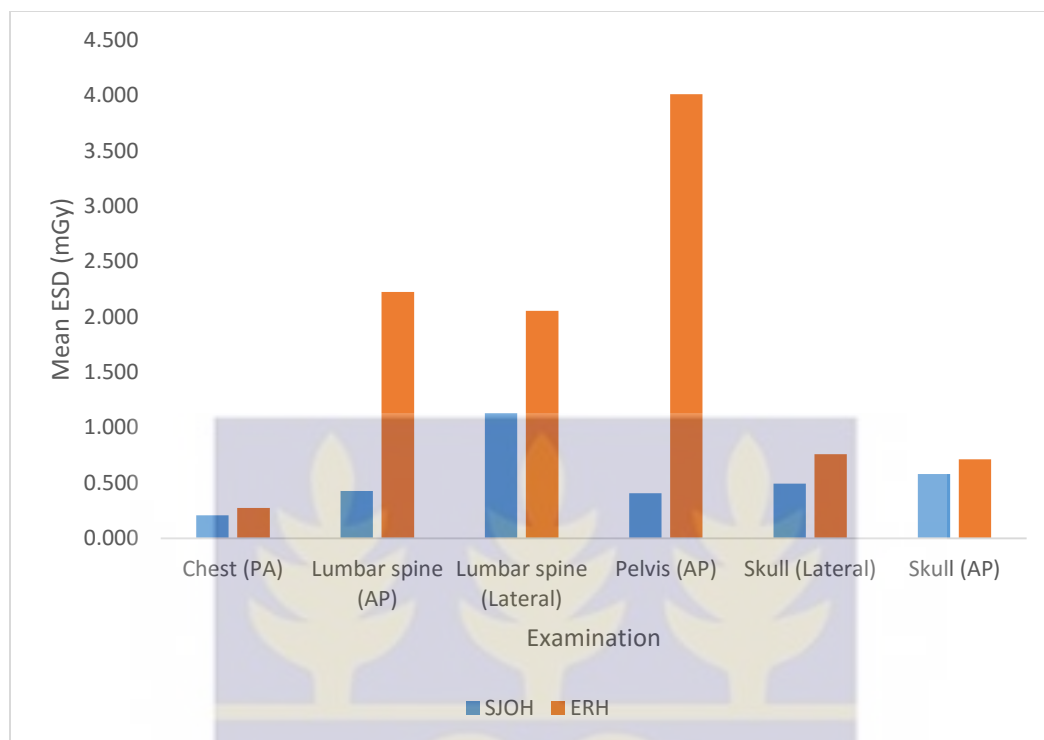


Figure 4. 8. Mean ESD for the selected examinations among the selected facilities

From Figure 4.8, ERH recorded the highest mean ESD of 4.014 ± 0.84 mGy for pelvis (AP) projection. The corresponding ESD at SJOH was 0.406 ± 0.03 mGy. There was a wide difference of 3.61 mGy, which was by a factor of 3 between the highest mean ESD recorded at ERH and the lowest mean ESD recorded at SJOH for pelvis. The higher mean ESD value recorded at ERH may be due to the selection of high exposure factors which was also based on the phantom anatomical thickness and body mass index. Lack of proper collimation of the radiation beam field may also be a cause.

Lumbar spine (AP) accounted for the second highest mean ESD value of 2.227 ± 0.79 mGy recorded at ERH from Figure 4.8. Corresponding ESD for SJOH was estimated as 0.428 ± 0.08 mGy. The difference between the mean ESD value recorded at ERH and SJOH were by a factor of 2. The high dose could be due to high exposure factors which

has to do with the sizes of phantom of the lumbar spine (AP). Large collimation could also be a factor.

The third highest mean ESD was lumbar spine (lateral) of a value of 2.056 ± 1.56 mGy for ERH and 1.131 ± 0.28 mGy for SJOH from Figure 4.8. The difference between the mean ESD value recorded at ERH and SJOH were by a factor of 1. But the exposure is on a higher side and might be attributed to high exposure, phantom anatomical thickness and not properly collimated.

As illustrated from Figure 4.8, the minimum and maximum mean ESD for skull (lateral) are 0.495 ± 0.14 mGy and 0.760 ± 0.08 mGy for SJOH and ERH respectively. The difference between them was 0.265 mGy. The difference for SJOH and ERH for skull (AP) was 0.133 mGy which is very close to the difference of skull (lateral). Good practice of radiation protection was adhered to and therefore dose to phantom was minimized.

From Figure 4.8, the last mean ESD was the chest (PA). The mean ESD for chest (AP) are 0.207 ± 0.10 mGy and 0.275 ± 0.09 mGy for SJOH and ERH respectively. The figures of the mean ESD clearly demonstrate the low exposure factors and good collimation of the radiation beam sizes to the chest (AP).

The range of mean ESD values for each projection in each participating hospitals for the selected examinations are presented in Figure 4.9.

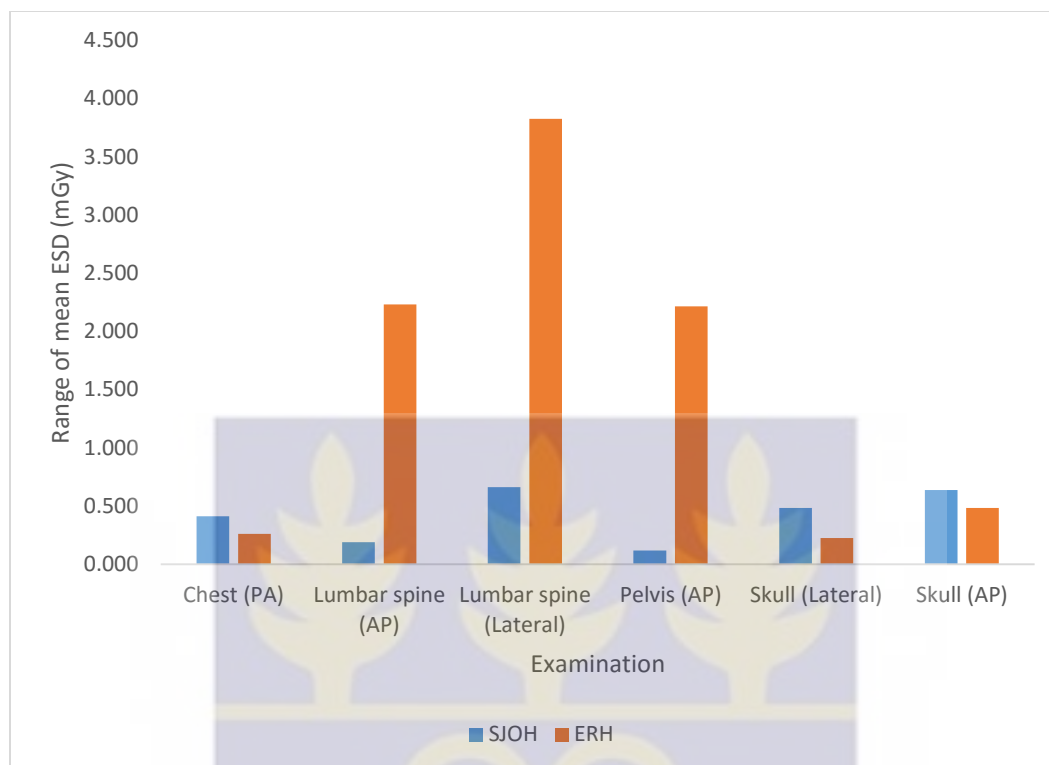


Figure 4. 9. Mean ESD values for the selected examination at the two hospitals

The range of ESDs for this study as shown in Figure 4.9 was determined by finding the difference between the maximum and the minimum mean ESD values recorded for individual examinations.

The results in Figure 4.9 show a large difference in the range of mean ESD values at ERH. The highest range was observed for the examination of the lumbar spine, at which ERH recorded mean ESD of 3.825 mGy and SJOH recorded mean ESD of 0.663 mGy. This accounts for the usage of different exposure factors and techniques even for the same examination.

From Figure 4.9, mean ESDs are higher at ERH with values of 2.233 mGy and 2.214 mGy as compared to mean ESDs at SJOH with values of 0.189 mGy and 0.117 mGy

for the lumbar spine AP and pelvis AP examinations respectively. The reason could be because the lower mean ESD may have been exposed by low exposure and well collimated which was good for both lumbar and the pelvis in SJOH in order not to over expose the sensitive organs.

The remaining three examinations (chest PA, skull Lateral and skull AP) recorded lower doses during the exposure of the phantom. SJOH recorded slightly higher doses than ERH for the three examinations. Low exposure parameters and good collimation could be the reasons for the low doses recorded.

4.3.5. Comparison of mean ESDs with international reference dose values

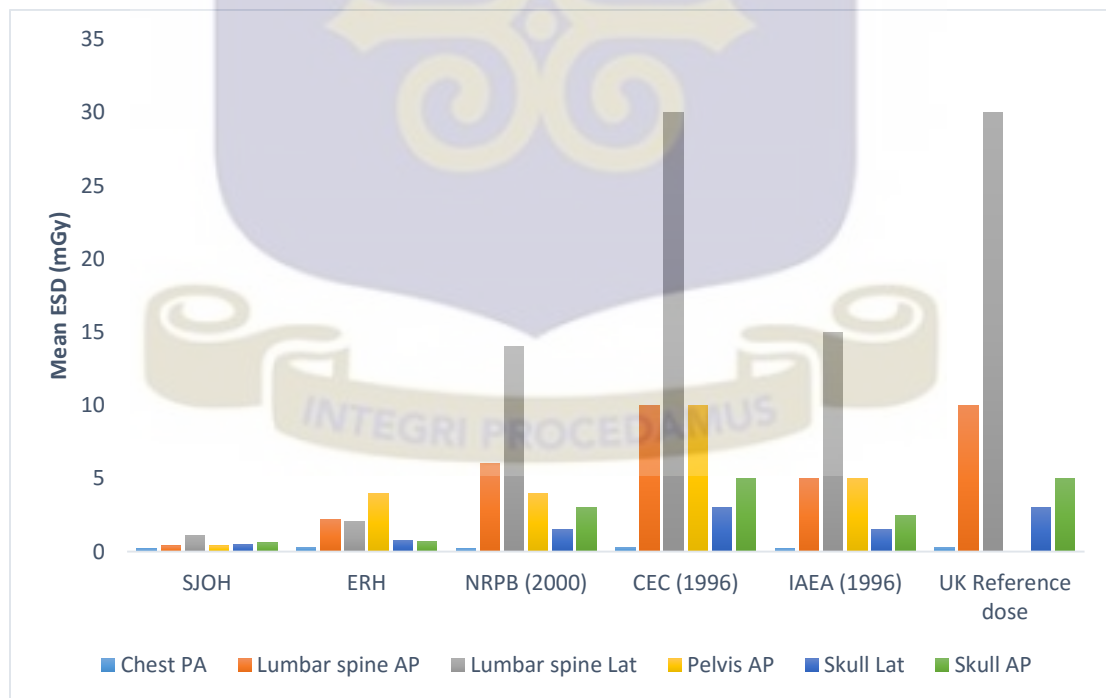


Figure 4. 10. Comparison of mean ESDs obtained in the present work with some international reference dose values (in mGy).

The results of comparison of mean ESDs obtained in the present work with some international reference dose values (in mGy) are presented in Figure 4.10. With the exception of chest PA examinations at ERH, all other measured ESDs were found to be within the corresponding DRLs recommended by NRPB, CEC, IAEA and UK. The mean ESD of 0.3 mGy for chest PA examination at ERH is higher than the corresponding mean ESD for NRPB and IAEA by a difference of 0.1 mGy. The variations in ESDs among the different radiological departments studied may be attributed to several factors: exposure parameters, radiological technique and accuracies of the (TLD) dosimeters used. Also, the efficiency of the X-ray generator in the department, FFD and total filtration that may be considered. The contribution of the phantom size to the mean ESD variability has been well established in the selection criteria adopted in this study that did not impose weight restriction. Weight measurements performed shows that the dose increases as weight increases (Mooney et al., 1998). The relative low dose levels found in this study could be attributed to a number of factors. In patient dosimetry in diagnostic radiology, dose measurements are normally made for standard sized patient or phantom, i.e. of weight close to 70 kg, and for a statistical significant number of patients, i.e. a minimum of 10 patients per room (NRPB, 1992). These requirements were rarely fulfilled in the present study. Moreover, unacceptable overexposed images were excluded from the study.

Several factors could have positively contributed to the results. Equipment performance can be a major factor, as relatively new equipment were reported to be in use. Moreover, almost all departments were found to be using filtration above the minimum requirements of 2.5 mm Al equivalent, with the least X-ray unit filtration of 2.8 mmAl (Parry et al, 1999).

4.4. Analysis of radiation risk to patients

Dose results obtained with the PCXMC calculations are used to estimate the stochastic radiation risks, age-dependent mortality rates and also for subsequent assessment of lifetime cancer risk. The BEIR VII committee has derived risk models called linear no-threshold model for both cancer incidence and cancer mortality. The models take into account the cancer site, sex, age at the exposure and attained age. Presently, low dose rates and small doses are believed to yield a relatively lower cancer risk compared to high dose rates and large doses (BEIR, 2006). This reduction in risk is accounted for by the dose and dose rate reduction factor (DDREF). The excess risk values are the basis of the lifetime risk estimates of patient that show variation for different patient dimensions and radiographic parameters. The use of the PCXMC provided relevant information that would suggest a revision and optimization of radiographic techniques aiming the reduction of patient doses.

4.4.1. Cancer risk assessment for the diagnostic examinations

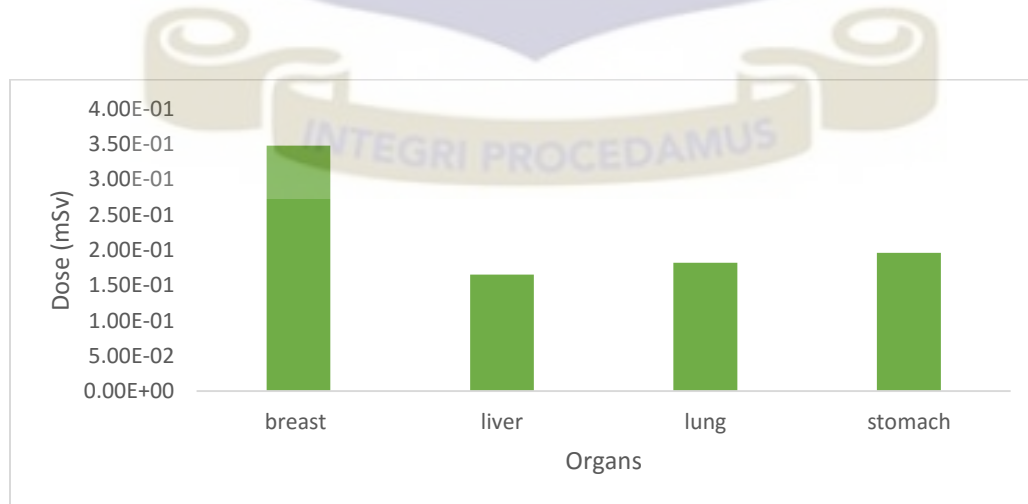


Figure 4. 11. Organ doses for chest PA examination

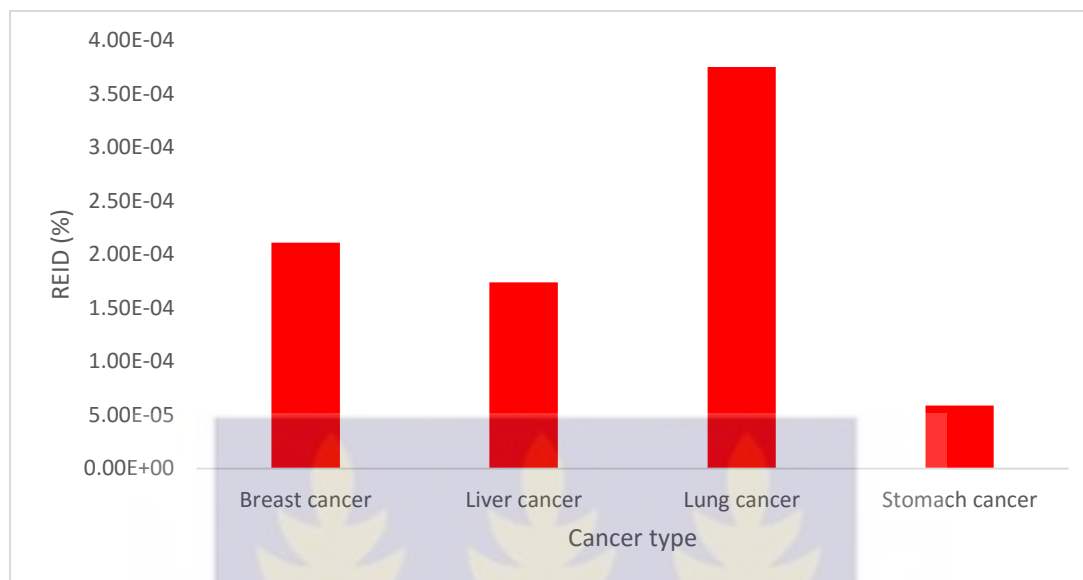


Figure 4. 12. Risk of exposure - induced cancer death of organs for chest PA examination

The results of organ doses and risk of exposure-induced cancer death (REID) of organs for chest PA examination are presented in Figures 4.11 and 4.12 respectively. It is evidenced that the breast received the highest dose of $3.48\text{E-}01$ mSv, followed by the stomach, lungs and liver with $1.96\text{E-}01$ mSv, $1.82\text{E-}01$ mSv and $1.65\text{E-}01$ mSv respectively. In terms of risk assessment for the organs, the lungs recorded the highest risk of exposure-induced cancer death of $3.75\text{E-}04\%$, followed by breast, stomach and liver with $2.11\text{E-}04\%$, $5.88\text{E-}05\%$ and $1.74\text{E-}05\%$ respectively.

Normally, low dose rates and small doses are believed to yield a relatively lower cancer risk compared to high dose rates and large doses (BEIR, 2006). However, from Figure 4.11, the analogy does not follow the trend. This is because the higher dose in the breast of $3.48\text{E-}01$ mSv more than lungs of $1.82\text{E-}01$ mSv should trigger higher risk of cancer in the breast than in the lung, but the lung possesses higher risk as compared to the

breast, and this is attributed to their tissue weighting factors (W_T) (ICRP, 2007). The tissue weighting factor accounts for the variable radio sensitivities of organs and tissues in the body to ionizing radiation.

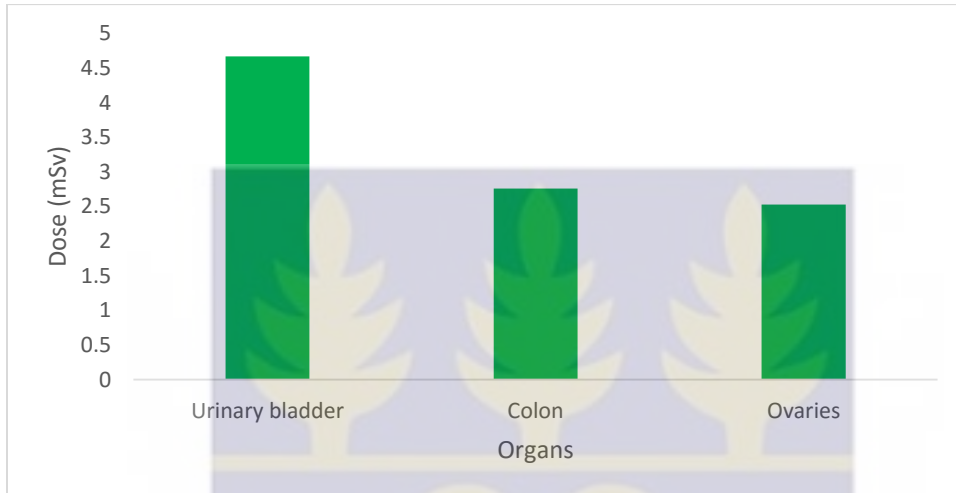


Figure 4. 13. Organ doses for pelvis AP examination

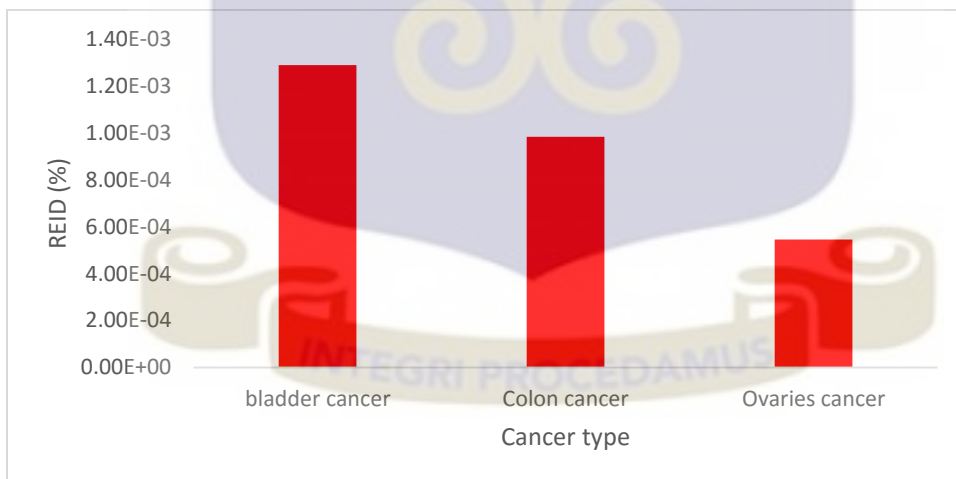


Figure 4. 14. Risk of exposure - induced cancer death of organs for pelvis AP examination

The results of organ doses and risk of exposure-induced cancer death of organs for pelvis AP examination are presented in Figures 4.13 and 4.14 respectively. It is observed

that the urinary bladder received the highest dose of 4.67 mSv, followed by the colon and ovary with 2.76 mSv and 2.53 mSv respectively. In terms of risk assessment for the organs, the bladder recorded the highest risk of exposure-induced cancer death of 1.29E-03%, followed by colon of 9.83E-04% and ovary of 5.45E-04%. Normally, low dose rates and small doses are believed to yield a relatively lower cancer risk compared to high dose rates and large doses (BEIR, 2006). The urinary bladder, colon and ovaries in Figure 4.13 with their respective risks of cancer type in Figure 4.14 followed the trend of lower doses resulting in lower risk and higher doses delivering higher risk. Besides the quantum of radiation dose delivered, weighting factors of tissues contribute significantly to the measure of the risk of stochastic effects.

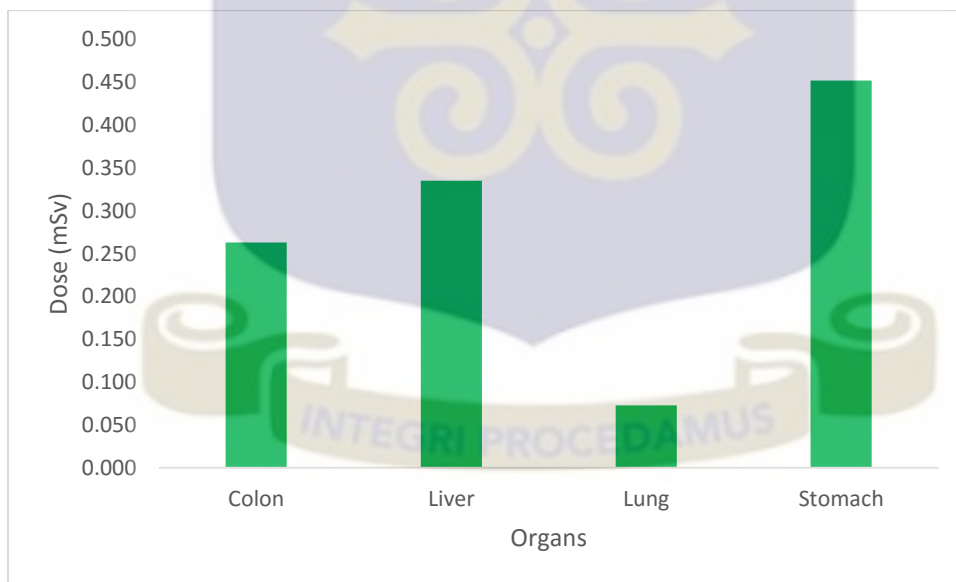


Figure 4. 15. Organ doses for skull examination

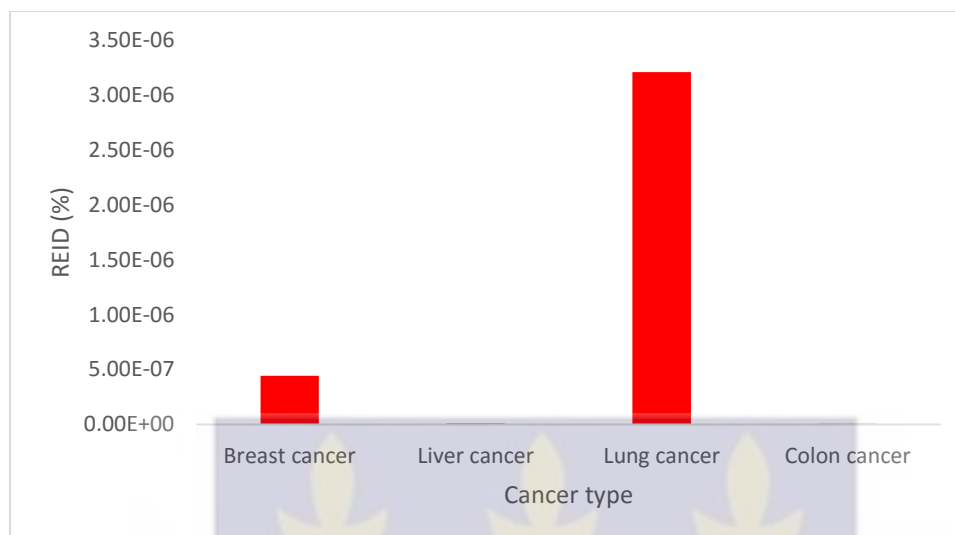


Figure 4. 16. Risk of exposure - induced cancer death of organs for skull examination

The results of organ doses and risk of exposure-induced cancer death of organs for skull examination are presented in Figures 4.15 and 4.16 respectively. From Figure 4.16, the lungs recorded the highest dose of $1.56\text{E-}03$ mSv, followed by the breast, liver and colon with $7.35\text{E-}04$ mSv, $1.05\text{E-}04$ mSv and $2.20\text{E-}05$ mSv respectively. For the organ risk assessment, the lungs received the highest risk of $3.21\text{E-}06\%$ followed by breast with $4.45\text{E-}07\%$, liver with $1.11\text{E-}08\%$ and colon with $7.84\text{E-}09\%$ in Figure 4.16. From the analogy, higher doses give higher risk and lower doses give lower risk (BEIR, 2006), the lungs with the higher dose followed by breast, liver and colon have their respective risks increases with the lung cancer, followed by breast cancer, liver cancer and colon cancer accordingly.

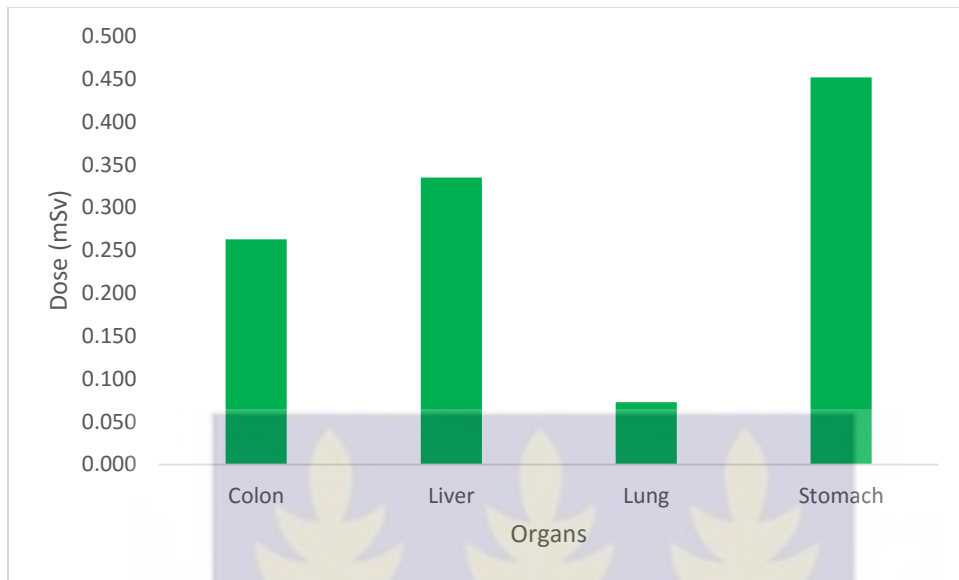


Figure 4. 17. Organ doses for lumbar spine examination

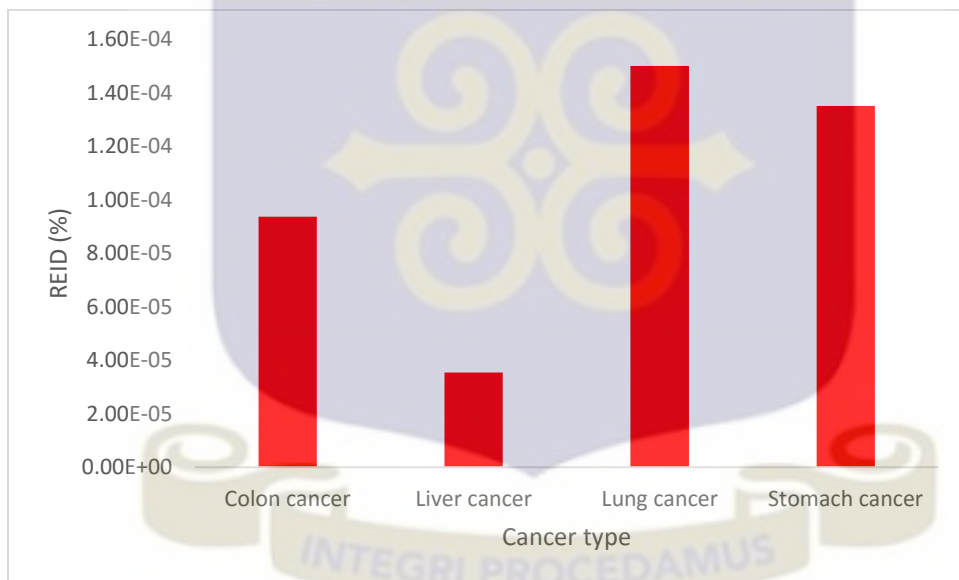


Figure 4. 18. Risk of exposure - induced cancer death of organs for lumbar spine examination

The results of organ doses and risk of exposure-induced cancer death for lumbar spine examinations are presented in Figures 4.17 and 4.18 respectively. From Figure 4.17, the stomach recorded the highest dose of 0.452 mSv, followed by liver, colon and lungs

with 0.335 mSv, 0.263 mSv and 0.073 mSv respectively. In terms of the organs' risk, the lungs have the highest risk of 1.50E-04%, followed by stomach with 1.35E-04%, colon with 9.36E-05% and liver with 3.54E-05% in Figure 4.18. The following organs; lungs, stomach and colon have the highest with tissue risk weighting factors of 0.12 as compared to liver which has the moderate risk with tissue weighting factor of 0.05. The lung cancer becomes the highly rated risk in comparison with stomach and colon due to its high radiosensitivity from Figure 4.18.

Table 4. 16. Age-dependent mortality rates for assessment of lifetime cancer risk for the two hospitals

Examination	ESDs(mGy)	REID (%)	LLE(hrs)	LLE/REID (years)	Effective dose/mSv
Chest PA	0.255	6.35E-04	1.9	35.0	0.096
	0.261	7.40E-04	2.2	34.6	0.112
	0.287	8.41E-04	2.5	34.0	0.133
Pelvis AP	2.632	2.18E-03	4.5	23.4	0.640
	4.568	3.90E-03	8.0	23.5	1.158
	4.846	4.17E-03	8.6	23.6	1.240
Skull	0.633	6.51E-05	0.2	29.5	0.014
	0.727	2.01E-04	0.5	30.8	0.042
	0.965	1.16E-04	0.3	29.7	0.024
Lumbar spine	1.491	7.29E-04	1.6	25.7	0.170
	2.210	2.16E-03	4.8	25.1	0.515
	3.290	1.60E-03	3.5	24.6	0.366

ESD – Entrance surface dose

REID – Risk of exposure-induced cancer death

LLE – Loss of life expectancy

LLE/REID – Loss of life expectancy per risk of exposure-induced cancer death

Table 4.16 shows the age-dependent mortality rates for assessment of lifetime cancer risk for the two hospitals. For the chest PA examination, the highest risk of exposure induced cancer death recorded was $8.41\text{E-}04\%$ with ESD of 0.287 mGy at 2.5 hours loss of life expectancy which is the difference between the expectation of life for a person exposed at age e and of an unexposed person who was alive at that age. The ESD of 0.261 mGy and 0.255 mGy, gave an estimated risk of $7.40\text{E-}04\%$ and $6.35\text{E-}04\%$ and their loss of life expectancies of 2.2 hours and 1.9 hours respectively. An increased in ESD from 0.255 mGy to 0.287 mGy directly increased the LLE from 1.9 hours to 2.5 hours respectively. Meaning more dose to patient increases the loss of life expectancy and reduce the lifespan of the patient. The loss of life expectancy per risk of exposure induced cancer is the average length of life lost per excess cancer death. The increased in the ESD from 0.255 mGy to 0.287 mGy causes the LLE/REID to decrease from 35.0 years to 34.0 years due to the increased in LLE from 1.9 hours to 2.5 hours respectively.

For the pelvis AP examination, the $4.17\text{E-}03\%$ was the highest risk of exposure induced cancer death recorded with 4.846 mGy of ESD at 8.6 hours loss of life expectancy. The ESD of 2.632 mGy and 4.568 mGy, produced an estimated risk of $2.18\text{E-}03\%$ and $3.90\text{E-}03\%$ respectively. This however increases the loss of life expectancy from 4.5 hours to 8.0 hours. The increases in loss of life expectancy have an adverse effect on the life of the patient exposed by causing its lifespan to reduce. The increase in loss of life expectancy per risk of exposure induced cancer from 23.4 years to 23.6 years is due to the increase in the ESD from 2.632 mGy to 4.846 mGy respectively. As the ESD increases, the loss of life expectancy increases and that further causes the increase in loss of life expectancy per risk of exposure induced cancer death.

For the skull examination, the highest risk of exposure induced cancer death recorded was $1.16\text{E-}04\%$ with ESD of 0.965 mGy at 0.3 hours loss of life expectancy. The ESD of 0.727 mGy and 0.633 mGy, produced an estimated risk of $2.01\text{E-}04\%$ and $6.51\text{E-}05\%$. This however increases the loss of life expectancy of 0.727 mGy by 0.5 hours and decreases the loss of life expectancy of 0.633 mGy by 0.2 hours. Meaning more dose to patient increases the loss of life expectancy and reduce the lifespan of the patient. The increased in the ESD from 0.633 mGy to 0.965 mGy causes the loss of life expectancy per risk of exposure induced cancer to increase from 29.5 years to 29.7 years accordingly.

For the lumbar spine examination, the highest risk of exposure induced cancer death recorded was $1.60\text{E-}03\%$ with ESD of 3.290 mGy at 3.5 hours loss of life expectancy. The ESD of 2.210 mGy and 1.491 mGy, gave an estimated risk of $2.16\text{E-}03\%$ and $7.29\text{E-}04\%$. This however increases the loss of life expectancy of 2.210 mGy by 4.8 hours and decreases the loss of life expectancy of 1.491 mGy by 1.6 hours with increase in loss of life expectancy per risk of exposure induced cancer at 25.1 years and 25.7 years respectively.

In summary, the increase of entrance surface dose turns to increase organs doses, the risk of exposure-induced cancer death, loss of life expectancy and loss of life expectancy per risk of exposure induced cancer death.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.0. Introduction

The Chapter presents the conclusions from the study and recommendations relevant to the findings.

5.1. Conclusions

ESDs from selected X-ray examination of the chest (PA), lumbar spine (AP/lateral), skull (AP/lateral) and pelvis (AP) in the two hospitals in the Eastern Region of Ghana have been measured by adult female anthropomorphic phantom for the four examinations. The mean ESDs values ranged from a minimum of 0.2 mGy to a maximum of 2.2 mGy. These values were all found to be within DRLs established by NRPB, CEC, IAEA and UK. However, the mean ESDs for the chest (PA) (0.3 mGy) measured in the Eastern Regional Hospital was found to be higher than NRPB (0.2 mGy) and IAEA (0.2 mGy) reference doses.

The results of the quality control tests performed on the two digital X-ray machines indicated that they were operating self-consistently within the acceptable criteria. The findings of this work is a very useful contribution towards the national effort to establish DRLs for digital radiography for the selected common examinations.

5.2. Recommendations

5.2.1. To Hospital

The health institutions should be retraining their radiographers through conferences, workshops and refresher courses to improve their knowledge and skills on selection of examination techniques factors to minimize patient doses consistent with acceptable image quality. Radiographers should keep records of exposure parameters used during X-ray examinations for retrospective patient dose estimation to be possible.

5.2.2. Regulatory Authority.

The regulatory authority should provide applicable regulations and guidance document on radiation protection and safe use of Digital Radiography in Ghana. The regulatory authority in collaboration with the relevant professional bodies should assist in establishing diagnostic reference levels for all examinations performed using Digital Radiography in Ghana



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APPENDIX A

Table A. 1. Measurement of ESDs of the chest pa with TLDs from SJOH

kVp	mAs	FS (cm ²)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
65	1.8	30 x 34	18	180	162	0.0860	0.1061	0.0961
65	1.8	30 x 34	18	180	162	0.1860	0.1061	0.1461
65	1.8	30 x 34	18	180	162	0.1860	0.0161	0.1011
65	1.8	30 x 34	18	180	162	0.0860	0.0161	0.0511
66	2.5	30 x 32	18	180	162	0.0810	0.0525	0.0667
66	2.5	30 x 32	18	180	162	0.1038	0.1074	0.1056
66	2.5	30 x 32	18	180	162	0.1038	0.0525	0.0781
66	2.5	30 x 32	18	180	162	0.0810	0.1074	0.0942
66	2.5	30 x 32	18	180	162	0.1810	0.0525	0.1167
66	2.5	30 x 32	18	180	162	0.0810	0.1525	0.1167
70	2	30 x 35	18	180	162	0.1048	0.0708	0.0878
70	2	30 x 35	18	180	162	0.1048	0.1708	0.1378
70	2.8	30 x 32	18	180	162	0.0952	0.0851	0.0901
70	2.8	30 x 32	18	180	162	0.1479	0.6781	0.4130
70	2.8	30 x 32	18	180	162	0.1952	0.0851	0.1401
70	2.8	30 x 32	18	180	162	0.0952	0.1851	0.1401
70	2.8	30 x 32	18	180	162	0.1479	0.5781	0.3630
70	2.8	30 x 32	18	180	162	0.2479	0.6781	0.4630
75	2.5	30 x 32	18	180	162	0.1166	0.1654	0.1410
75	2.5	30 x 32	18	180	162	0.2166	0.1654	0.1910
75	2.5	30 x 32	18	180	162	0.2166	0.2654	0.2410
78	1.8	31 x 32	18	180	162	0.3433	0.1886	0.2659
78	1.8	31 x 32	18	180	162	0.4361	0.2227	0.3294
78	1.8	31 x 32	18	180	162	0.4361	0.3227	0.3794
78	1.8	31 x 32	18	180	162	0.3433	0.2886	0.3159
80	2	34 x 41	18	180	162	0.3375	0.3420	0.3398
80	2	34 x 41	18	180	162	0.3365	0.3420	0.3393
80	2	34 x 41	18	180	162	0.3433	0.3420	0.3426
80	3.2	30 x 32	18	180	162	0.1759	0.2044	0.1901
80	3.2	30 x 32	18	180	162	0.2759	0.2044	0.2401
80	3.2	30 x 32	18	180	162	0.2759	0.1044	0.1901
80	2.2	31 x 32	18	180	162	0.2962	0.2103	0.2532
80	2.2	31 x 32	18	180	162	0.2963	0.2103	0.2533
80	2.2	31 x 32	18	180	162	0.2962	0.2203	0.2582
82	2	31 x 32	18	180	162	0.1680	0.1641	0.1660
82	2	31 x 32	18	180	162	0.1680	0.1651	0.1665

82	2	31 x 32	18	180	162	0.1680	0.1654	0.1667
82	2	31 x 32	18	180	162	0.1457	0.1922	0.1690
82	2	31 x 32	18	180	162	0.1457	0.2022	0.1740
82	2	31 x 32	18	180	162	0.1574	0.2022	0.1798
84	2.8	32 x 33	18	180	162	0.2403	0.2205	0.2304
84	2.8	32 x 33	18	180	162	0.2403	0.3205	0.2804
84	2.8	32 x 33	18	180	162	0.2413	0.3205	0.2809

Table A. 2. Measurement of ESDs of the lumbar spine AP with TLDs from SJOH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
70	4.5	9 x 25	16	100	84	0.3075	0.3307	0.3191
70	8	8 x 31	16	100	84	0.2832	0.3760	0.3296
70	8	8 x 31	16	100	84	0.3832	0.3760	0.3796
70	4.5	9 x 25	16	100	84	0.4175	0.3317	0.3746
76	6.3	12 x 45	16	100	84	0.5001	0.5040	0.5020
76	6.3	12 x 45	16	100	84	0.5101	0.5040	0.5070
76	6.3	12 x 45	16	100	84	0.5101	0.5051	0.5076
76	6.3	12 x 45	16	100	84	0.5001	0.5051	0.5026

Table A. 3. Measurement of ESDs of the lumbar spine lateral with TLDs from SJOH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
80	6.3	8 X 23	24	100	76	0.7557	0.6963	0.7260
80	6.3	8 x 23	24	100	76	0.7557	0.7963	0.7760
80	6.3	8 x 23	24	100	76	0.7657	0.7963	0.7810
80	6.3	8 x 23	24	100	76	0.7657	0.6963	0.7310
80	6.3	8 x 23	24	100	76	0.7657	0.6963	0.7310
85	12.5	10 x 36	24	100	76	1.1889	1.4797	1.3343
85	12.5	10 x 36	24	100	76	1.1989	1.4797	1.3393
85	12.5	10 x 36	24	100	76	1.1989	1.5797	1.3893
85	12.5	10 x 36	24	100	76	1.1889	1.5797	1.3843
85	12.5	10 x 36	24	100	76	1.1989	1.4797	1.3393
88	10	21 x 45	24	100	76	1.3077	1.1993	1.2535
88	10	21 x 45	24	100	76	1.3177	1.1993	1.2585
88	10	21 x 45	24	100	76	1.3177	1.2993	1.3085

88	10	21 x 45	24	100	76	1.3177	1.2993	1.3085
88	10	21 x 45	24	100	76	1.2993	1.3077	1.3035

Table A. 4. Measurement of ESDs of the pelvis AP with TLDs from SJOH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
60	4.5	35 X 43	21	100	79	0.4524	0.3350	0.3937
60	4.5	35 X 43	21	100	79	0.4524	0.3450	0.3987
60	4.5	35 X 43	21	100	79	0.4524	0.4350	0.4437
60	4.5	35 X 43	21	100	79	0.4624	0.3350	0.3987
60	4.5	35 X 43	21	100	79	0.4624	0.4350	0.4487
65	5	35 x 37	21	100	79	0.4206	0.3896	0.4051
65	5	35 x 37	21	100	79	0.4206	0.4896	0.4551
65	5	35 x 37	21	100	79	0.4306	0.3896	0.4101
65	5	35 x 37	21	100	79	0.4306	0.4896	0.4601
65	5	35 x 37	21	100	79	0.4226	0.3896	0.4061
66	5	33 x 37	21	100	79	0.3171	0.4194	0.3683
66	5	33 x 37	21	100	79	0.3271	0.4194	0.3733
66	5	33 x 37	21	100	79	0.3271	0.4294	0.3783
66	5	33 x 37	21	100	79	0.3171	0.4294	0.3733
66	5	33 x 37	21	100	79	0.4171	0.4290	0.4231
68	5	32 x 39	21	100	79	0.3289	0.3571	0.3430
68	5	32 x 39	21	100	79	0.4289	0.4571	0.4430
68	5	32 x 39	21	100	79	0.3289	0.4571	0.3930
68	5	32 x 39	21	100	79	0.3389	0.4572	0.3981
68	5	32 x 39	21	100	79	0.3489	0.4572	0.4031

Table A. 5. Measurement of ESDs of the skull lateral with TLDs from SJOH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
66	4	26 x 27	16	100	84	0.2561	0.2686	0.2623
66	4	26 x 27	16	100	84	0.3561	0.2686	0.3124
66	4	26 x 27	16	100	84	0.3561	0.3686	0.3624
66	4	26 x 27	16	100	84	0.2561	0.3686	0.3124
70	4	24 x 25	16	100	84	0.4975	0.5920	0.5448
70	4	24 x 25	16	100	84	0.5975	0.5920	0.5948
70	4	24 x 25	16	100	84	0.4975	0.5950	0.5463

70	4	24 x 25	16	100	84	0.4995	0.5950	0.5473
70	5.6	24 x 25	16	100	84	0.6737	0.7171	0.6954
70	5.6	24 x 25	16	100	84	0.7737	0.7171	0.7454
70	5.6	24 x 25	16	100	84	0.6737	0.6171	0.6454
70	5.6	24 x 25	16	100	84	0.6737	0.6517	0.6627
70	8	23 x 27	16	100	84	0.5805	0.1926	0.3865
70	8	23 x 27	16	100	84	0.5805	0.2926	0.4366
70	8	23 x 27	16	100	84	0.5805	0.2926	0.4366
70	8	23 x 27	16	100	84	0.6805	0.2926	0.4866
70	8	23 x 27	16	100	84	0.6805	0.1926	0.4366

Table A. 6. Measurement of ESDs of the skull AP with TLDs from SJOH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
70	6.3	17 x 23	18	100	82	0.4415	0.4571	0.4493
70	6.3	17 x 23	18	100	82	0.5415	0.4571	0.4993
70	6.3	17 x 23	18	100	82	0.5415	0.5571	0.5493
70	6.3	17 x 23	18	100	82	0.4415	0.5571	0.4993
72	6.3	19 x 27	18	100	82	0.9363	0.9679	0.9521
72	6.3	19 x 27	18	100	82	0.9463	0.9679	0.9571
72	6.3	19 x 27	18	100	82	0.9463	0.9879	0.9671
72	6.3	19 x 27	18	100	82	0.9363	0.9879	0.9621
72	6.3	19 x 27	18	100	82	0.9563	0.9877	0.9720
75	5	17 x 25	18	100	82	0.3787	0.3177	0.3482
75	5	17 x 25	18	100	82	0.4787	0.3177	0.3982
75	5	17 x 25	18	100	82	0.4787	0.4177	0.4482
75	7.1	18 x 23	18	100	82	0.3678	0.2984	0.3331
75	7.1	18 x 23	18	100	82	0.3678	0.3984	0.3831
75	7.1	18 x 23	18	100	82	0.4678	0.3984	0.4331
75	7.1	18 x 23	18	100	82	0.4678	0.2984	0.3831
80	5	17 x 23	18	100	82	0.4509	0.4876	0.4692
80	5	17 x 23	18	100	82	0.5509	0.4876	0.5193
80	5	17 x 23	18	100	82	0.5509	0.5876	0.5693
80	5	17 x 23	18	100	82	0.4509	0.5876	0.5193

APPENDIX B

Table B. 1. Measurement of ESDs of the chest pa with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
80	4	36 x 37	18	150	132	0.2900	0.2198	0.2549
80	4	36 x 37	18	150	132	0.3000	0.2298	0.2649
80	4	36 x 37	18	150	132	0.2800	0.2098	0.2449
80	4	36 x 37	18	150	132	0.2800	0.2098	0.2449
80	4	36 x 37	18	150	132	0.2800	0.2098	0.2449
80	4	36 x 37	18	150	132	0.2800	0.2098	0.2449
80	4	36 x 37	18	150	132	0.2800	0.2098	0.2449
80	4	36 x 37	18	150	132	0.3000	0.2298	0.2649
80	4	36 x 37	18	150	132	0.3000	0.2298	0.2649
80	4	36 x 37	18	150	132	0.3000	0.2298	0.2649
80	4	36 x 37	18	150	132	0.3000	0.2298	0.2649
80	4	36 x 37	18	150	132	0.2900	0.2198	0.2549
90	3.2	36 x 37	18	150	132	0.3990	0.3702	0.3846
90	3.2	36 x 37	18	150	132	0.2536	0.4328	0.3432
90	3.2	36 x 37	18	150	132	0.4090	0.3602	0.3846
90	3.2	36 x 37	18	150	132	0.4090	0.3602	0.3846
90	3.2	36 x 37	18	150	132	0.4090	0.3602	0.3846
90	3.2	36 x 37	18	150	132	0.4090	0.3602	0.3846
90	3.2	36 x 37	18	150	132	0.4090	0.3602	0.3846
90	3.2	36 x 37	18	150	132	0.2536	0.4328	0.3432
90	3.2	36 x 37	18	150	132	0.2536	0.4328	0.3432
90	3.2	36 x 37	18	150	132	0.2536	0.4328	0.3432
90	3.2	36 x 37	18	150	132	0.3990	0.3702	0.3846
90	3.2	36 x 37	18	150	132	0.3990	0.3702	0.3846
90	3.2	36 x 37	18	150	132	0.3990	0.3702	0.3846
100	1.8	39 x 41	18	150	132	0.1277	0.1180	0.1229
100	1.8	39 x 41	18	150	132	0.1592	0.0973	0.1283
100	1.8	39 x 41	18	150	132	0.9658	0.1572	0.5615
100	1.8	33 x 37	18	150	132	0.3824	0.1908	0.2866
100	1.8	33 x 37	18	150	132	0.1963	0.2510	0.2237
100	1.8	39 x 41	18	150	132	0.1277	0.1180	0.1229
100	1.8	39 x 41	18	150	132	0.1277	0.1180	0.1229

100	1.8	39 x 41	18	150	132	0.1277	0.1180	0.1229
100	1.8	39 x 41	18	150	132	0.1592	0.0973	0.1283
100	1.8	39 x 41	18	150	132	0.1592	0.0973	0.1283
100	1.8	39 x 41	18	150	132	0.1592	0.0973	0.1283
100	1.8	33 x 37	18	150	132	0.3824	0.1908	0.2866
100	1.8	33 x 37	18	150	132	0.3824	0.1908	0.2866
100	1.8	33 x 37	18	150	132	0.3824	0.1908	0.2866
100	1.8	33 x 37	18	150	132	0.1963	0.2510	0.2237
102	2	36 x 37	18	150	132	0.2850	0.2367	0.2608
102	2	36 x 37	18	150	132	0.2671	0.2522	0.2596
102	2	36 x 37	18	150	132	0.2950	0.2267	0.2608
102	2	36 x 37	18	150	132	0.2771	0.2422	0.2596
102	2	36 x 37	18	150	132	0.2850	0.2367	0.2608
102	2	36 x 37	18	150	132	0.2850	0.2367	0.2608
102	2	36 x 37	18	150	132	0.2850	0.2367	0.2608
102	2	36 x 37	18	150	132	0.2671	0.2522	0.2596
102	2	36 x 37	18	150	132	0.2671	0.2522	0.2596
102	2	36 x 37	18	150	132	0.2671	0.2522	0.2596
102	2	36 x 37	18	150	132	0.2950	0.2267	0.2608
102	2	36 x 37	18	150	132	0.2950	0.2267	0.2608
102	2	36 x 37	18	150	132	0.2950	0.2267	0.2608
102	2	36 x 37	18	150	132	0.2771	0.2422	0.2596
102	2	36 x 37	18	150	132	0.2771	0.2422	0.2596

Table B. 2. Measurement of ESDs of the lumbar spine AP with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
80	22	17 x 46	16	100	84	1.0030	1.1237	1.0634
80	22	12 x 32	16	100	84	1.2058	1.2604	1.2331
80	22	12 x 32	16	100	84	1.4247	1.5567	1.4907
80	22	17 x 46	16	100	84	1.0030	1.1237	1.0634
80	22	17 x 46	16	100	84	1.0030	1.1237	1.0634
80	22	17 x 46	16	100	84	1.0030	1.1237	1.0634
80	22	17 x 46	16	100	84	1.0030	1.1237	1.0634
80	22	12 x 32	16	100	84	1.2058	1.2604	1.2331
80	22	12 x 32	16	100	84	1.2058	1.2604	1.2331
80	22	12 x 32	16	100	84	1.2058	1.2604	1.2331
80	22	12 x 32	16	100	84	1.2058	1.2604	1.2331
80	22	12 x 32	16	100	84	1.4247	1.5567	1.4907
80	22	12 x 32	16	100	84	1.4247	1.5567	1.4907

80	22	12 x 32	16	100	84	1.4247	1.5567	1.4907
80	22	12 x 32	16	100	84	1.4247	1.5567	1.4907
92	36	14 x 48	16	100	84	2.1047	2.3150	2.2099
92	36	14 x 48	16	100	84	2.1147	2.3050	2.2099
92	36	14 x 48	16	100	84	2.1247	2.2950	2.2099
92	36	14 x 48	16	100	84	2.1047	2.3150	2.2099
92	36	14 x 48	16	100	84	2.1047	2.3150	2.2099
92	36	14 x 48	16	100	84	2.1047	2.3150	2.2099
92	36	14 x 48	16	100	84	2.1047	2.3150	2.2099
92	36	14 x 48	16	100	84	2.1147	2.3050	2.2099
92	36	14 x 48	16	100	84	2.1147	2.3050	2.2099
92	36	14 x 48	16	100	84	2.1147	2.3050	2.2099
92	36	14 x 48	16	100	84	2.1247	2.2950	2.2099
92	36	14 x 48	16	100	84	2.1247	2.2950	2.2099
92	36	14 x 48	16	100	84	2.1247	2.2950	2.2099
92	36	14 x 48	16	100	84	2.1247	2.2950	2.2099
96	40	10 x 33	16	100	84	3.5435	3.0482	3.2959
96	40	10 x 33	16	100	84	2.3809	3.6125	2.9967
96	40	10 x 33	16	100	84	3.5535	3.0382	3.2959
96	40	10 x 33	16	100	84	2.3909	3.6025	2.9967
96	40	10 x 33	16	100	84	3.5435	3.0482	3.2959
96	40	10 x 33	16	100	84	3.5435	3.0482	3.2959
96	40	10 x 33	16	100	84	3.5435	3.0482	3.2959
96	40	10 x 33	16	100	84	2.3809	3.6125	2.9967
96	40	10 x 33	16	100	84	2.3809	3.6125	2.9967
96	40	10 x 33	16	100	84	2.3809	3.6125	2.9967
96	40	10 x 33	16	100	84	3.5535	3.0382	3.2959
96	40	10 x 33	16	100	84	3.5535	3.0382	3.2959
96	40	10 x 33	16	100	84	3.5535	3.0382	3.2959
96	40	10 x 33	16	100	84	2.3909	3.6025	2.9967
96	40	10 x 33	16	100	84	2.3909	3.6025	2.9967
96	40	10 x 33	16	100	84	2.3909	3.6025	2.9967

Table B. 3. Measurement of ESDs of the lumbar spine lateral with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
80	22	17 x 46	24	100	76	1.2988	1.6273	1.4631
80	22	14 x 37	24	100	76	1.9395	1.9291	1.9343
80	22	14 x 37	24	100	76	2.4206	2.2874	2.3540

80	22	17 x 46	24	100	76	1.2988	1.6273	1.4631
80	22	17 x 46	24	100	76	1.2988	1.6273	1.4631
80	22	14 x 37	24	100	76	1.9395	1.9291	1.9343
80	22	14 x 37	24	100	76	1.9395	1.9291	1.9343
80	22	14 x 37	24	100	76	2.4206	2.2874	2.3540
80	22	14 x 37	24	100	76	2.4206	2.2874	2.3540
80	22	17 x 46	24	100	76	1.2988	1.6273	1.4631
80	22	17 x 46	24	100	76	1.2988	1.6273	1.4631
80	22	14 x 37	24	100	76	1.9395	1.9291	1.9343
80	22	14 x 37	24	100	76	1.9395	1.9291	1.9343
80	22	14 x 37	24	100	76	2.4206	2.2874	2.3540
80	22	14 x 37	24	100	76	2.4206	2.2874	2.3540
92	36	14 x 48	24	100	76	0.0984	0.1147	0.1066
92	36	14 x 48	24	100	76	0.1984	0.1247	0.1616
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.0984	0.1147	0.1066
92	36	14 x 48	24	100	76	0.0984	0.1147	0.1066
92	36	14 x 48	24	100	76	0.1984	0.1247	0.1616
92	36	14 x 48	24	100	76	0.1984	0.1247	0.1616
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.1984	0.1247	0.1616
92	36	14 x 48	24	100	76	0.1984	0.1247	0.1616
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
92	36	14 x 48	24	100	76	0.2984	0.2347	0.2666
96	40	10 x 33	24	100	76	4.2275	3.6364	3.9320
96	40	10 x 33	24	100	76	4.2389	3.6125	3.9257
96	40	10 x 33	24	100	76	4.2375	3.6264	3.9320
96	40	10 x 33	24	100	76	4.2389	3.6025	3.9207
96	40	10 x 33	24	100	76	4.2275	3.6364	3.9320
96	40	10 x 33	24	100	76	4.2275	3.6364	3.9320
96	40	10 x 33	24	100	76	4.2275	3.6364	3.9320
96	40	10 x 33	24	100	76	4.2389	3.6125	3.9257
96	40	10 x 33	24	100	76	4.2389	3.6125	3.9257
96	40	10 x 33	24	100	76	4.2389	3.6125	3.9257
96	40	10 x 33	24	100	76	4.2375	3.6264	3.9320
96	40	10 x 33	24	100	76	4.2375	3.6264	3.9320
96	40	10 x 33	24	100	76	4.2375	3.6264	3.9320
96	40	10 x 33	24	100	76	4.2389	3.6025	3.9207
96	40	10 x 33	24	100	76	4.2389	3.6025	3.9207
96	40	10 x 33	24	100	76	4.2389	3.6025	3.9207

Table B. 4. Measurement of ESDs of the pelvis AP with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
90	32	33 x 37	21	100	79	2.2421	3.0219	2.6320
90	32	28 x 33	21	100	79	3.1326	2.6832	2.9079
90	32	28 x 33	21	100	79	3.4394	2.8353	3.1374
90	32	33 x 37	21	100	79	2.2421	3.0219	2.6320
90	32	33 x 37	21	100	79	2.2421	3.0219	2.6320
90	32	28 x 33	21	100	79	3.1326	2.8353	2.9840
90	32	28 x 33	21	100	79	3.1326	2.8353	2.9840
90	32	28 x 33	21	100	79	3.4394	2.8353	3.1374
90	32	28 x 33	21	100	79	3.4394	2.8353	3.1374
90	32	33 x 37	21	100	79	2.2421	3.0219	2.6320
90	32	33 x 37	21	100	79	2.2421	3.0219	2.6320
90	32	28 x 33	21	100	79	3.1326	2.6832	2.9079
90	32	28 x 33	21	100	79	3.1326	2.6832	2.9079
90	32	28 x 33	21	100	79	3.4394	2.8353	3.1374
90	32	28 x 33	21	100	79	3.4394	2.8353	3.1374
92	36	29 x 37	21	100	79	4.6474	5.0445	4.8460
92	36	29 x 37	21	100	79	4.6574	5.0345	4.8460
92	36	29 x 37	21	100	79	4.7474	4.9445	4.8460
92	36	29 x 37	21	100	79	4.6474	5.0445	4.8460
92	36	29 x 37	21	100	79	4.6474	5.0445	4.8460
92	36	29 x 37	21	100	79	4.6574	5.0345	4.8460
92	36	29 x 37	21	100	79	4.6574	5.0345	4.8460
92	36	29 x 37	21	100	79	4.7474	4.9445	4.8460
92	36	29 x 37	21	100	79	4.7474	4.9445	4.8460
92	36	29 x 37	21	100	79	4.6474	5.0445	4.8460
92	36	29 x 37	21	100	79	4.6474	5.0445	4.8460
92	36	29 x 37	21	100	79	4.6574	5.0345	4.8460
92	36	29 x 37	21	100	79	4.6574	5.0345	4.8460
92	36	29 x 37	21	100	79	4.7474	4.9445	4.8460
92	36	29 x 37	21	100	79	4.7474	4.9445	4.8460
98	40	30 x 36	21	100	79	3.8554	4.1105	3.9830
98	40	30 x 36	21	100	79	3.6384	5.4980	4.5682
98	40	30 x 36	21	100	79	3.8654	4.1005	3.9830
98	40	30 x 36	21	100	79	3.6484	5.4880	4.5682
98	40	30 x 36	21	100	79	3.8554	4.1105	3.9830
98	40	30 x 36	21	100	79	3.8554	4.1105	3.9830
98	40	30 x 36	21	100	79	3.8554	4.1105	3.9830

98	40	30 x 36	21	100	79	3.6384	5.4980	4.5682
98	40	30 x 36	21	100	79	3.6384	5.4980	4.5682
98	40	30 x 36	21	100	79	3.6384	5.4980	4.5682
98	40	30 x 36	21	100	79	3.8654	4.1005	3.9830
98	40	30 x 36	21	100	79	3.8654	4.1005	3.9830
98	40	30 x 36	21	100	79	3.8654	4.1005	3.9830
98	40	30 x 36	21	100	79	3.6484	5.4880	4.5682
98	40	30 x 36	21	100	79	3.6484	5.4880	4.5682
98	40	30 x 36	21	100	79	3.6484	5.4880	4.5682

Table B. 5. Measurement of ESDs of the skull lateral with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
70	12.5	22 x 26	16	100	84	0.6228	0.7478	0.6853
70	14	24 x 27	16	100	84	0.8716	0.7527	0.8121
70	14	24 x 27	16	100	84	0.9041	0.8729	0.8885
70	14	23 x 27	16	100	84	0.6151	0.9675	0.7913
70	14	23 x 27	16	100	84	0.6407	0.7109	0.6758
70	14	24 x 28	16	100	84	0.6635	0.7376	0.7006
70	12.5	22 x 26	16	100	84	0.6228	0.7478	0.6853
70	12.5	22 x 26	16	100	84	0.6228	0.7478	0.6853
70	14	24 x 27	16	100	84	0.8716	0.7527	0.8121
70	14	24 x 27	16	100	84	0.8716	0.7527	0.8121
70	14	24 x 27	16	100	84	0.9041	0.8729	0.8885
70	14	24 x 27	16	100	84	0.9041	0.8729	0.8885
70	14	23 x 27	16	100	84	0.6151	0.9675	0.7913
70	14	23 x 27	16	100	84	0.6151	0.9675	0.7913
70	14	24 x 28	16	100	84	0.6407	0.7109	0.6758
70	14	24 x 28	16	100	84	0.6407	0.7109	0.6758
70	14	24 x 28	16	100	84	0.6635	0.6635	0.6635
70	14	24 x 28	16	100	84	0.6635	0.7376	0.7006
70	14	24 x 27	16	100	84	0.8816	0.7427	0.8121
70	14	24 x 27	16	100	84	0.9141	0.8629	0.8885
70	14	23 x 27	16	100	84	0.6251	0.9575	0.7913
70	14	23 x 27	16	100	84	0.6507	0.7009	0.6758
70	14	24 x 28	16	100	84	0.6735	0.7276	0.7006
70	12.5	22 x 26	16	100	84	0.6328	0.7378	0.6853
70	12.5	22 x 26	16	100	84	0.6328	0.7378	0.6853
70	14	24 x 27	16	100	84	0.8816	0.7427	0.8121
70	14	24 x 27	16	100	84	0.8816	0.7427	0.8121

70	14	24 x 27	16	100	84	0.9141	0.8629	0.8885
70	14	24 x 27	16	100	84	0.9141	0.8629	0.8885
70	14	23 x 27	16	100	84	0.6251	0.9575	0.7913
70	14	23 x 27	16	100	84	0.6251	0.9575	0.7913
70	14	23 x 27	16	100	84	0.6507	0.7009	0.6758
70	14	23 x 27	16	100	84	0.6507	0.7009	0.6758
70	14	24 x 28	16	100	84	0.6735	0.7276	0.7006
70	14	24 x 28	16	100	84	0.6735	0.7276	0.7006

Table B. 6. Measurement of ESDs of the skull AP with TLDs from ERH

kVp	mAs	FS (cm)	PAT (cm)	FDD (cm)	FSD (cm)	TLD 1	TLD 2	AvESD(mGy)
70	12.5	19 x 25	18	100	82	0.6575	0.7957	0.7266
70	14	18 x 23	18	100	82	0.6291	0.6367	0.6329
70	14	18 x 23	18	100	82	0.9121	1.0180	0.9650
70	14	20 x 26	18	100	82	0.5729	0.5395	0.5562
70	14	20 x 26	18	100	82	0.4736	0.5069	0.4902
70	14	18 x 25	18	100	82	0.7023	1.0803	0.8913
70	12.5	19 x 25	18	100	82	0.6675	0.7957	0.7316
70	14	18 x 23	18	100	82	0.6391	0.6367	0.6379
70	14	18 x 23	18	100	82	0.9221	1.0180	0.9700
70	14	20 x 26	18	100	82	0.5829	0.5395	0.5612
70	14	20 x 26	18	100	82	0.4836	0.5069	0.4952
70	14	18 x 25	18	100	82	0.7123	1.0803	0.8963
70	12.5	19 x 25	18	100	82	0.6575	0.8057	0.7316
70	14	18 x 23	18	100	82	0.6291	0.6467	0.6379
70	14	18 x 23	18	100	82	0.9121	1.0280	0.9700
70	14	20 x 26	18	100	82	0.5729	0.5495	0.5612
70	14	20 x 26	18	100	82	0.4736	0.5169	0.4952
70	14	18 x 25	18	100	82	0.7023	1.0903	0.8963
70	12.5	19 x 25	18	100	82	0.6675	0.7857	0.7266
70	14	18 x 23	18	100	82	0.6391	0.6267	0.6329
70	14	18 x 23	18	100	82	0.9221	1.0080	0.9650
70	14	20 x 26	18	100	82	0.5829	0.5295	0.5562
70	14	20 x 26	18	100	82	0.4836	0.4969	0.4902
70	14	18 x 25	18	100	82	0.7123	1.0703	0.8913
70	12.5	19 x 25	18	100	82	0.6475	0.8057	0.7266
70	14	18 x 23	18	100	82	0.6191	0.6467	0.6329
70	14	18 x 23	18	100	82	0.9021	1.0280	0.9650
70	14	20 x 26	18	100	82	0.6291	0.5495	0.5893

70	14	20 x 26	18	100	82	0.4636	0.5169	0.4902
70	14	18 x 25	18	100	82	0.6923	1.0903	0.8913



