

**ASSESSMENT OF DESIGN AND SHIELDING IN SOME SELECTED  
CONVENTIONAL X-RAY AND COMPUTED TOMOGRAPHY (CT) FACILITIES  
IN BURKINA FASO**

**BY**

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## DECLARATION

### Candidate's Declaration

This thesis is the result of research work undertaken by ABDOULAYE SAWADOGO in the Department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. CYRIL SCHANDORF and Prof. J.J. FLETCHER.

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We hereby declare that the preparation and presentation of this thesis were supervised in accordance with guidelines on supervision of thesis laid down by the University of Ghana.

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## ABSTRACT

The main objective of this work is to assess the integrity of structural shielding to validate the protection of the staff and the public for two selected general radiography and CT facilities. The assessment for general radiography was based on 729 examinations for facility A and 706 examinations for facility B. For computed tomography (CT) rooms, a total of 293 body and 190 head procedures were used for facility A, and 195 body and 160 head procedures for facility B. For general radiography, the workload distribution and the normalized workload per patient have been determined for each room type (floor and chest-bucky). For facility A, the normalized workload per patient was  $0.96 \text{ mA min patient}^{-1}$  for the floor and  $1.25 \text{ mA min patient}^{-1}$  for the chest-bucky, the unshielded primary air-kerma per patient for the floor was  $2.56 \text{ mGy patient}^{-1}$  and  $3.4 \text{ mGy patient}^{-1}$  for the chest-bucky in the general radiography room. The average DLP were  $1830 \pm 610 \text{ mGy cm}$  and  $859 \pm 438 \text{ mGy cm}$  for head and body respectively in the CT room. For facility B, the normalized workload per patient was  $1.14 \text{ mA min patient}^{-1}$  for the floor and  $0.53 \text{ mA min patient}^{-1}$  for the chest-bucky, the unshielded primary air-kerma per patient was  $3.13$  for the floor and  $1.9$  for the chest-bucky in general radiography room. The average DLP were  $806 \pm 346 \text{ mGy cm}$  and  $305 \pm 154 \text{ mGy cm}$  for head and body respectively in the CT room. For both of these facilities, the calculated barrier thicknesses are smaller than the existing barrier thicknesses. Dose rate measurements confirmed that the different barriers thicknesses are enough to maintain the dose received by workers and the public below the recommended dose limits.

## DEDICATION

This research work is dedicated to my lovely wife Aoua and my wonderful son Emran Daanish, my sisters Safiatou and Djamila and to my uncle Boukary.



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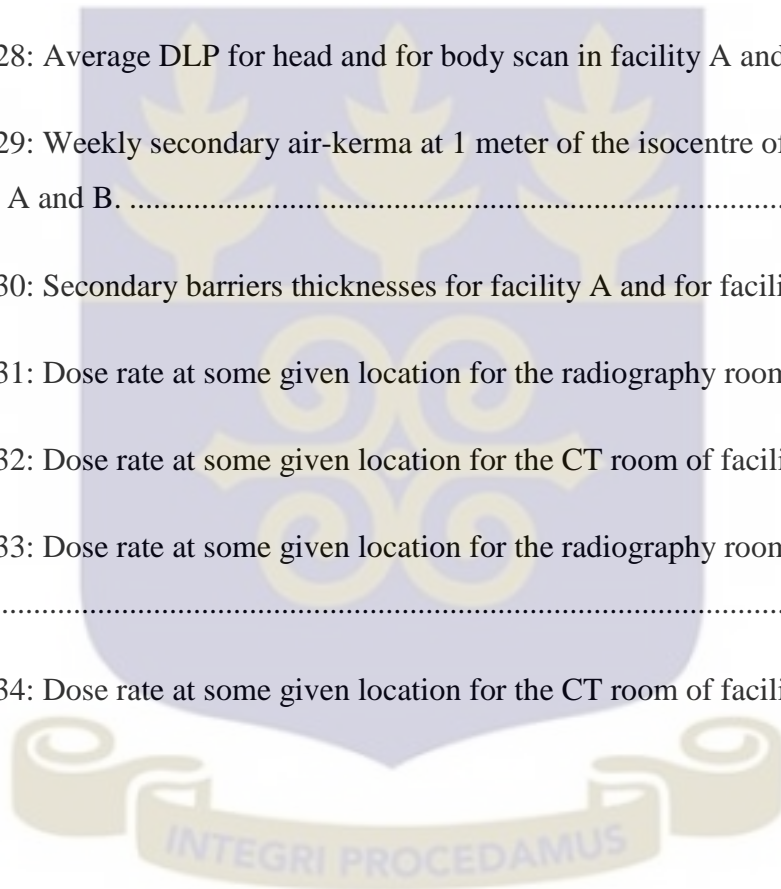
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## LIST OF ABBREVIATIONS AND SYMBOLS

AAPM	American Association of Physicists in Medicine
AutoCAD	Computer-aided design
$\alpha_1$	Scatter fraction per primary beam area at 1 m primary distance
B	Broad beam transmission
$B_{housing}$	Transmission of leakage radiation through x-ray tube housing
BIR	British Institute of Radiology
CT	Computed Tomography
$CTDI_{Vol}$	Computed Tomography Dose Index Volume
d	Distance from a radiation source to an occupied area
DAP	dose-area product
DLP	Dose-Length Product
$d_{pri}$	Primary distance
$d_{sec}$	Secondary distance
ESD	entrance surface dose
FFD	Focus-Film-Distance
F	Primary beam field area at primary beam distance $d_F$
Gy	gray

HVL	Half-Value Layer
ICRP	International Commission on Radiological Protection
IPEM	Institute of Physics and Engineering in Medicine
ISL	Inverse Square Law
Kerma	kinetic energy released per unit mass
kVp	kilovolt peak
$K_L$	Leakage air-kerma at 1 m from source
$K_S$	Air-kerma in an occupied area due to scattered radiation
$K_P^1$	Unshielded primary air kerma per patient at 1 m from the source
$K_W^1$	Air-kerma at 1 m per unit workload due to primary beam
mAs	milliampere-seconds
NCRP	National on Radiation Protection and Measurements
N	Number of patients per week undergoing x-ray procedures
P	Shielding design goal
QA	Quality Assurance
QC	Quality Control
Sv	sievert
SID	Source to Image Distance
T	Occupancy (factor)

TVL	Ten-Value Layer
U	Use factor
W	Workload
$W_{norm}$	Normalized workload per patient



## CHAPTER ONE

### INTRODUCTION

#### 1.1. BACKGROUND

X-rays are an important tool in medical diagnosis and therapy. However, if the x-rays are not shielded such that they only interact with the intended locations, they are potentially hazardous to the workers, patients and members of the public [1]. Often the x-ray facilities used for diagnostic purposes in several third world countries are very few compared to the demand [2]. Because of high patient workload and less preventive maintenance, breakdowns are common. In addition to that most rooms used to host x-ray facilities were not originally intended for the purposes and are often smaller than the recommended standard floor area of 38 m<sup>2</sup> (Heath Building Note (Scottish office, 1994)) for general-purpose x-ray machines. Furthermore, the locations of x-ray machines are not optimized relative to the layouts of the rooms. The review for optimal shielding requirements in such cases is further complicated because the composition of the building materials used to construct most walls are precisely unknown.

The review of radiation shielding conditions is necessary when the designing assumptions change [3]. Of more interest is the review of the secondary barriers because of the higher occupancy than previously predicted. The National Council on Radiation Protection and measurements report number 49 (NCRP49) provides the widely accepted traditional methodology for radiation shielding designing [3]. This traditional technique for designing radiation barriers may be unrealistic because the assumptions made in shielding designing do not reflect the existing situations. It has

for example been established that these methods may underestimate or overestimate the scattered and leakage radiation respectively from modern x-ray units. As a result of the inherent limitations in the traditional methods, a new shielding concept recommended by NCRP-147 is therefore adopted to derive the radiation dose levels at selected points. Further to that, the NCRP-147 is chosen for use because it is one of the latest recommended shielding concepts for typical modern diagnostic x-ray and computed tomography units.

The aim of this study is therefore to compare the radiation doses calculated using the NCRP-147 model and area monitoring data prior to assess the shielding adequacy of the existing barriers.

## **1.2. STATEMENT OF THE PROBLEM**

In BURKINA FASO there are currently 77 conventional diagnostic x ray machines and 18 CT machines for a population around 17000000 residents. These machines operate in public and private hospitals and most of them are more than 5 years old. Changes may occur because of the following reasons:

- high patient workload
- un-attenuated primary and secondary radiation paths into control areas and other areas outside the X-ray facility;
- changes in equipment layout, room configuration or adjacent areas that would affect the shielding design;
- Impaired shielding due to the installation of electrical outlets plumbing or air conditioning ducts and so on [4].

There is therefore the need to assess the adequacy of the shielding at the design state of general Radiography and CT facility and periodically when any of the factors mentioned above changes. Such shielding evaluations of general Radiography and CT facilities have not been done in Burkina Faso. This thesis work is intended to do a retrospective evaluation of two selected general radiography and CT facilities in Burkina Faso. The data from this study may prompt similar studies to be carried out on the facilities in country.

### **1.3. OBJECTIVES**

The main objective of this work is to assess the integrity of structural shielding in order to validate the protection of the staff and the public at two selected general radiography and CT facilities in Burkina Faso.

The specific objectives will be to:

- Estimate the workload spectra for the facilities selected;
- Estimate shielding thicknesses for the primary and secondary barriers;
- Verify adequacy of shielding design to protect staff and the public;
- Make appropriate recommendations from the findings.

### **1.4. RELEVANCE AND JUSTIFICATION**

Exposure to X-ray emitted during the diagnostic imaging process presents a risk to patients, hospital staff, and the public. The effects of this exposure are known as stochastic effects and may induce cancer. The stochastic effect do not have a threshold of dose, but the probability of occurrence increases with the dose. To optimize the dose received by workers, the public and the patient, NCRP-147 [5] provides the methodology for assessing the structural shielding design for medial

X-ray Imaging facilities to verify the adequacy of the shielding that the systems provided.

However deficiencies in radiation shielding designs may arise due to insufficient or incorrect information available to the person preparing the design, complex operating techniques of the radiation apparatus, the repair or reinstallation of electrical outlets, plumbing or air conditioning ducts and so on can impaired the shielding integrity. For these reasons it is strongly recommended to assess the design and the shielding that will allow to optimize the dose received by the worker and the member of the public.

The results of this assessment will verify the structural shielding integrity, the average equivalent dose rate for controlled and supervised areas in line with NCRP-147 Report. This is important for the purpose of optimization of protection of workers and the public.

### **1.5. SCOPE AND LIMITATION**

This study is based on theoretical approach by calculating the required barriers thicknesses for two general radiography and two computed tomography rooms and compare them with the existing barriers thicknesses. The study is also aimed to assess the measures in place to protect staff, patients and the public against the harmful effect of ionizing radiation.

This work is the first attempt for the assessment of the design and shielding of diagnostic medical facility in Burkina Faso.

## 1.6. ORGANISATION OF THE THESIS

Chapter one introduces the background, the objectives, relevance and scope and limitation of the work. Chapter two presents the literature review on the methodology of radiation shielding for diagnostic imaging, based on British Institute of Radiology and the Institute of Physics and Engineering in Medicine (BIR/IPEM) works, NCRP-49 and NCRP-147 methods. The materials and methods are described in chapter three. Chapter four summarizes the results of this thesis and the discussion on the comparative values of the normalized workload, the primary and secondary unshielded air-kerma. The thesis ends with chapter five which provides the conclusion and some recommendations to the relevant stakeholders.



## **CHAPTER TWO**

### **2.0. LITERATURE REVIEW**

This chapter reviews the literature relevant on the methodology of radiation shielding for diagnostic imaging, based on BIR/IPEM works, NCRP-49 and NCRP-147 methods.

The use of radiation apparatus for health purposes may give rise to radiation dose or dose rates above the design limits. For this reason it is required to undertake an assessment to establish if any shielding or additional shielding is required to limit radiation exposures to employees and members of the public to an acceptable level.

The proper shielding of medical diagnostic x-ray rooms play a key role in protecting the workers and the members of the public. British Institute of Radiology (BIR) and the National Council on Radiation Protection and Measurements (NCRP), present guidelines for medical diagnostic x-ray shielding that form the basis for most countries in designing x-ray rooms and shielding.

This chapter discuss first the review of methods for design and shielding evaluation in conventional radiography, in computed tomography (CT), and in mammography room and ends by presenting the regulatory requirements for design and shielding in medical X-ray facilities.

#### **2.1. Review of Methods for design and shielding evaluation**

##### **2.1.1. Design and Shielding evaluation of conventional x-ray facilities**

#### 2.1.1.1 Design of the conventional X-ray room

Radiographic rooms are used in a more versatile manner than most other x-ray installations. Generally there are two main imaging stations: a table and a vertical Bucky stand used principally for chest radiography. Examinations on the table most commonly involve the radiation beam firing downwards with the cassette either in the Bucky tray or on the table top (generally for extremities). For these locations protection is required for the secondary radiation and for the transmitted primary radiation. The area of the wall or floor exposed to the latter component being both limited and predictable. However, other parts of the floor or walls may be exposed to transmitted primary beam, for example, to lateral views taken with the patient on the table and examination of patients on trolleys.

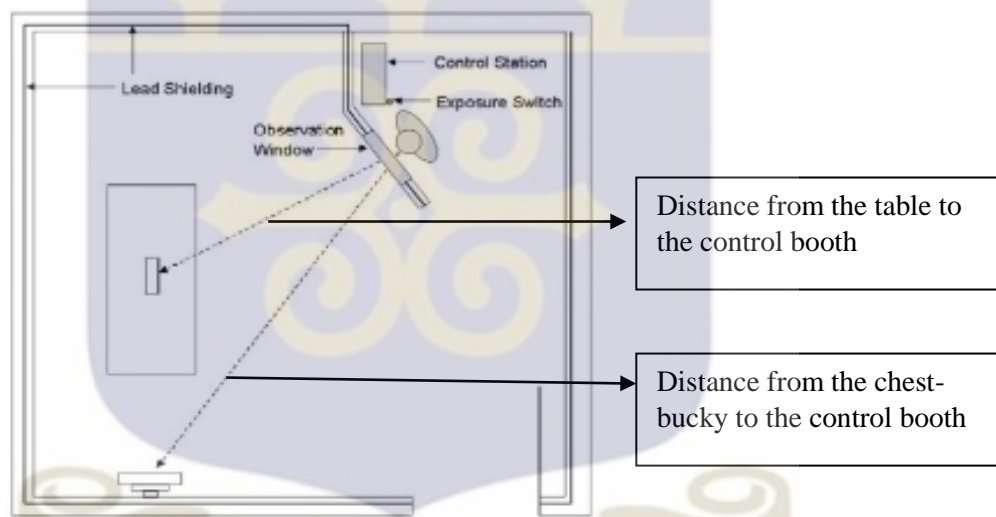
It is likely that protection will be required from both the transmitted primary and secondary radiation component. Certain radiographic techniques may make protection from unattenuated primary radiation necessary [6].

Provision shall be made for the operator to observe and communicate with the patient on the table or at the vertical cassette assembly. The operator of a radiographic unit shall remain in a protected area (control booth) or behind a fixed shield that will intercept the incident radiation. The control booth should not be used as a primary barrier. The exposure switch shall be positioned such that the radiographer cannot make an exposure with his or her body outside of the shielding area. This is generally accomplished if the X-ray exposure switch is at least 1 m from the edge of the control booth [5].

The control booth shall consist of a permanent structure at least 2.1 m high from the floor and should contain unobstructed floor space sufficient to allow safe operation of

the equipment. The booth shall be positioned so that no unattenuated primary or unattenuated single-scattered radiation will reach the operator's position in the booth.

The control booth shall have a window or viewing device that allows the operator to view the patient during all X-ray exposure performed in the room. The operator must be able to view the wall Bucky and X-ray table, as well as patients confined to stretchers. When an observation window is used, the window and frame shall provide the necessary attenuation required to reduce the air-kerma to the shielding design goal. The window(s) should be at least 45× 45 cm and centred 1.5 m above the finished floor [5]. A typical design for a control booth is illustrated in Figure 2.1:



**Figure 2.1: Typical design for a control booth in a radiographic X-ray room surrounded by occupied areas. Dashed lines indicated the required radiographer's line of sight to the X-ray table and wall Bucky. The exposure switch is positioned at least 1 m from the edge of the control booth.**

### 2.1.1.2 Shielding evaluation of conventional x-ray facilities

### **2.1.1.2.1 Methodology adopted by the joint BIR/IPEM working party**

#### **i. Design criteria**

The Ionising Radiations Regulations 1999 (IRR99) require that work involving exposure to external radiations should be performed in rooms which are provided with adequate shielding. Because of public access to the surrounding area or access of employees who are not directly involved in the work in x-ray rooms, the shielding should be design to reduce dose rates to the lowest level that is reasonably practicable. It is therefore necessary to formulate design criteria to ensure that this requirement is met [6].

The National Radiation Protection Board (NRPB) has based on [7] to recommend that the constraint on optimisation for a single source of radiation should not exceed 30% of the dose limit to public, in this case 0.3 mSv. They also emphasised that the introduction of dose constraints does not replace the requirement on operators to optimise their use of sources or their management of practices to ensure that exposures to members of the public are kept as low as reasonably achievable.

Dose constraints, therefore, represent an upper bound on the outcome of any optimisation procedure. However, there is also an acceptance that on-site exposures to members of the public should not be assessed in terms of either continuous occupancy or exposure. In terms of shielding, therefore, the application of the dose constraint must be made using realistic assumptions.

The Working Party considered the application of alternatives to the 0.3 mSv per annum dose constraint. If fewer than 10 exposures are made on each working day, or

if the equipment is used for a restricted number of days in the year, the limitation to a time averaged dose rate  $7.5 \mu\text{Sv h}^{-1}$  would represent the design constraint [6].

## ii. Occupancy factor

The application of the dose constraint must be made using realistic assumptions regarding the occupancy of areas which are relevant in terms of the shielding problem. To be realistic, the occupancy factor for an area should not be considered as being an indication of the time during which it is occupied by a generic group of people (such as patients in a waiting room). Instead, it is the fraction of time spent by the single person who is there the longest. In this context, it is most likely that the critical groups for shielding purposes will not be patients or patients' visitors but non radiation workers employed by the hospital. Given this assumption, the occupancy factor is best defined as being the fraction of an 8 hours day or 2000 hour year for which a particular area is occupied by a single person. The working party provides the values specifies in Table 2.1.



**Table 2.1: Some recommended occupancy factors provided by the BIR/IPEM working party [6].**

Location	Occupancy factor
Adjacent X-ray room	1
Reception area	1
Film reading area	1
Offices, shop, living quarter, children's indoor play area, occupied space in nearby buildings	1
Staff room	1
X-ray control room	1
Nurses' station	1
Patient examination and treatment rooms	1/2
Corridors	1/5
Wards, patient rooms	1/5
Toilets or bathrooms	1/10
Outdoor areas with seating	1/10
Storage rooms	1/20
Unattended vending areas	1/20
Patient changing room	1/20
Stairways	1/20
Unattended car parks	1/20
Unattended waiting rooms	1/20

### iii. Workload

A prerequisite to designing shielding for any x-ray facility is a knowledge of the use to which the room is going to be put and of the number of patients that are expected to be imaged in a year. This information will allow estimates of workload to be made. Without doubt, the best estimates of workload are those which take into account local practice, rather than generic figures which represent 'busy departments'. For example, the working party recommended that Dose Area Product (DAP) is used as the measure of workload. DAP can be estimated from the Entrance Surface Dose (ESD) measurement or calculation provided that relativistic field sizes and backscatter factors are available.

#### iv. Primary radiation

For primary radiation it is necessary to know which examination may involve the use of the horizontal beam. Most commonly, horizontal beams are used with the vertical Bucky with the patient standing or lying on a trolley. The vertical Bucky may be used for the following examinations:

- ✓ Chest (at between 60 and 150 kVp);
- ✓ Shoulder, cervical spines (at between 60 and 75 kVp);
- ✓ Abdomens (70-90kVp);
- ✓ Standing knees, femur (60-70 kVp);
- ✓ Spines (70-90 kVp).

#### v. Transmission calculation method

The maximum transmission (B) is given by

$$B = \frac{D_c}{K_{inc} \times T \times 52} \quad (2.1)$$

In which  $D_c$  is the annual dose constraint,  $K_{inc}$  is the kerma incident on the wall per week, and T is the occupancy factor. Film dose method and Entrance Surface Dose method are used for the calculation of the kerma incident on the wall per week ( $K_{inc}$ ).

Having the transmission, the required primary barrier thickness of lead and concrete are given through figure 2.2 and figure 2.3 respectively.

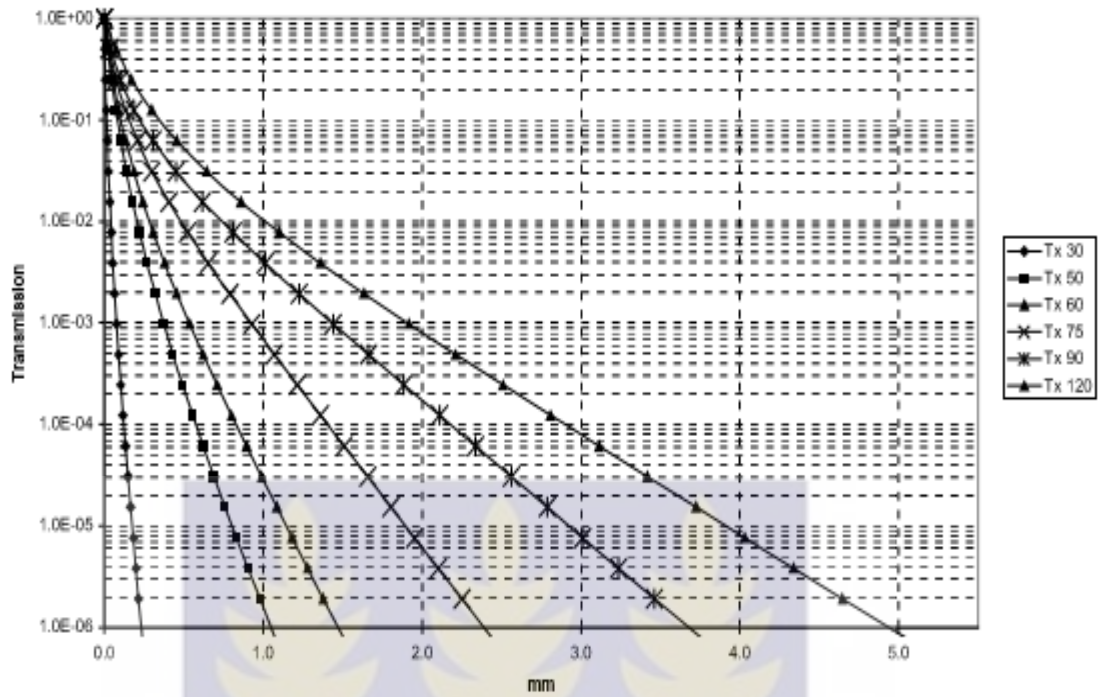


Figure 2.2.: Transmission of primary radiation through lead

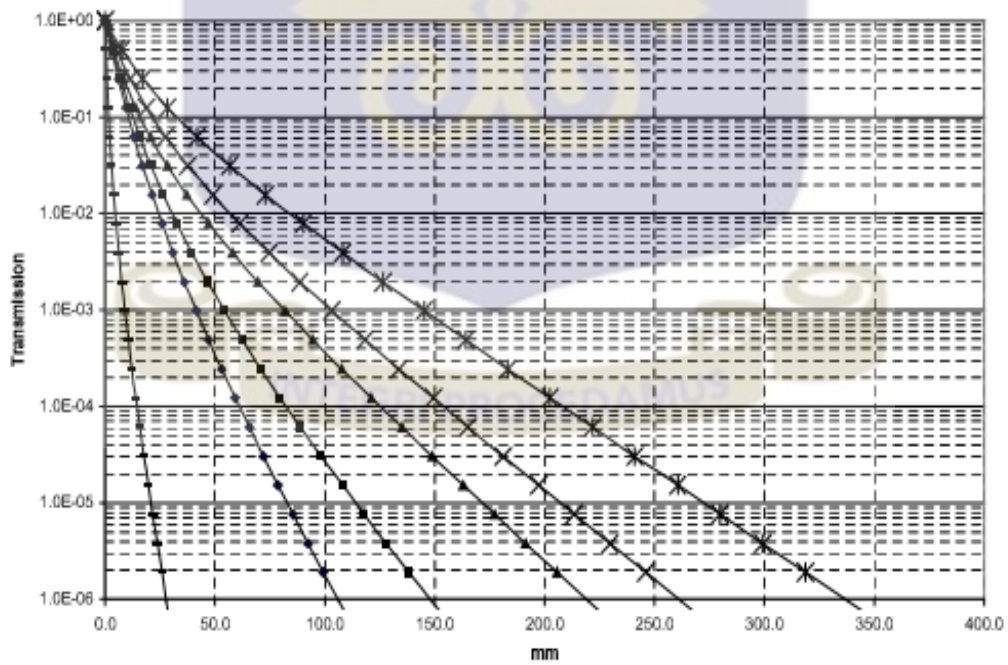


Figure 2.3: Transmission of primary radiation through concrete

**a) Film dose method**

The first of the clinical situations is that in which the X-ray beam is entirely intercepted by the patient. The shielding calculation can then be based on the incident film kerma.

400 speed radiographic film requires, by definition, a dose of 2.5  $\mu\text{Gy}$  to produce a density of 1.0 plus base plus fog. Some areas of the film will have higher densities because [6]:

- radiologists generally prefer somewhat darker films;
- the beam may be larger than the body part (for example for extremities), and
- There are density variations across the film.

In addition slower films may be used for extremities (although for protection purposes, these are associated with low kVps and are therefore of much less relevance).

When 400 speed film is used, it is proposed that a value of 10  $\mu\text{Gy}$  is taken as the maximum air-kerma incident on any part of the film cassette. If 200 speed class film is used, 20  $\mu\text{Gy}$  should be used. The use of 10  $\mu\text{Gy}$  as the kerma to the film is indicative of significant attenuation of the primary beam through the patient. Patient attenuation will vary from about  $10^{-3}$  for a lateral view of the lumbar spine with an Entrance Surface Dose (ESD) of 10 mGy to 0.1 for a chest radiograph with an ESD of 0.1 mGy. Making the assumption that the beam is fully collimated to the area of the cassette, there is then further attenuation produced in the cassette itself and in the structure of the cassette holder and the table base or vertical Bucky stand.

The kerma at the wall is given by:

$$K_{inc} = n \times K_{film} \times B_{film} \times \left(\frac{FFD}{FFD+d}\right)^2 \quad (2.2)$$

In which  $n$  is the number of films per week,  $K_{film}$  ( $=10\mu Gy$ ) is the film kerma,  $B_{film}$  ( $= 0.5$ ) is the transmission through the film and cassette,  $d$  is the distance from the film to the wall, and FFD is the focus-film distance.

### b) Entrance Surface Dose method

The second situation occurs where the beam passes outside the patient in, for example, skull radiography or extremity examinations. In this case it is recommended that the Kerma is calculated from ESD, taking into consideration primary attenuation factors for the cassette, table assembly, etc.

The primary Kerma at the wall per film ( $K$ ) in the absence of the Bucky can be calculated from the inverse square law (ISL):

$$K = ESD \times \left[\frac{FFD-d_f}{FFD+d_w}\right]^2 \quad (2.3)$$

In which ESD is the entrance surface dose,  $d_f$  is the entrance surface to film distance and  $d_w$  is the film-to-wall distance. Knowing the number of radiographic film in a week, the kerma incident in the wall per week ( $K_{inc}$ ) can easily be calculated by multiplying the kerma at the wall per film ( $K$ ) by the number of radiographic film per week. The transmission of the primary beam through a cassette and a film cassette is show in Table 2.2.

**Table 2.2: Transmission of primary radiation through a cassette and a film cassette plus grid (adapted from Dixon, 1994).**

	60 kVp	80 kVp	100 kVp	125 kVp
Primary transmission (cassette)	0.055	0.11	0.16	0.21
Lead equivalence of cassette (mm)	0.14	0.17	0.19	0.21
Primary transmission (cassette + grid)	0.028	0.068	0.10	0.14
Lead equivalence of cassette + grid (mm)	0.19	0.23	0.26	0.29

### 1. Geometries

Attenuation of primary beam needs to be estimated for three geometries:

- Table radiography with attenuation in the cassette plus table assembly;
- Cross table radiography with attenuation in the cassette alone;
- Vertical Bucky radiography with attenuation in the cassette plus Bucky assembly.

### 2. Quality Assurance (QA)

Some caution is required in adopting the film dose method. Performance testing procedure, as part of an overall quality assurance programme, are carried out at increasingly frequent intervals. Many test e.g. radiographic output, can involve relatively high doses, possibly several tens of mGy, delivered directly on the table top at possibly monthly intervals. This could be the largest contribution to the dose to the floor. It is therefore important to consider whether such measurements might have any impact on the floor shielding.

**vi. Secondary radiation**

Secondary radiation comprises a scatter component and a leakage component. Both components must be taken into account when considering the transmission of the secondary radiation. It is often assumed that the scattered radiation will have the same transmission properties as the primary beam whilst the leakage component will be harder.

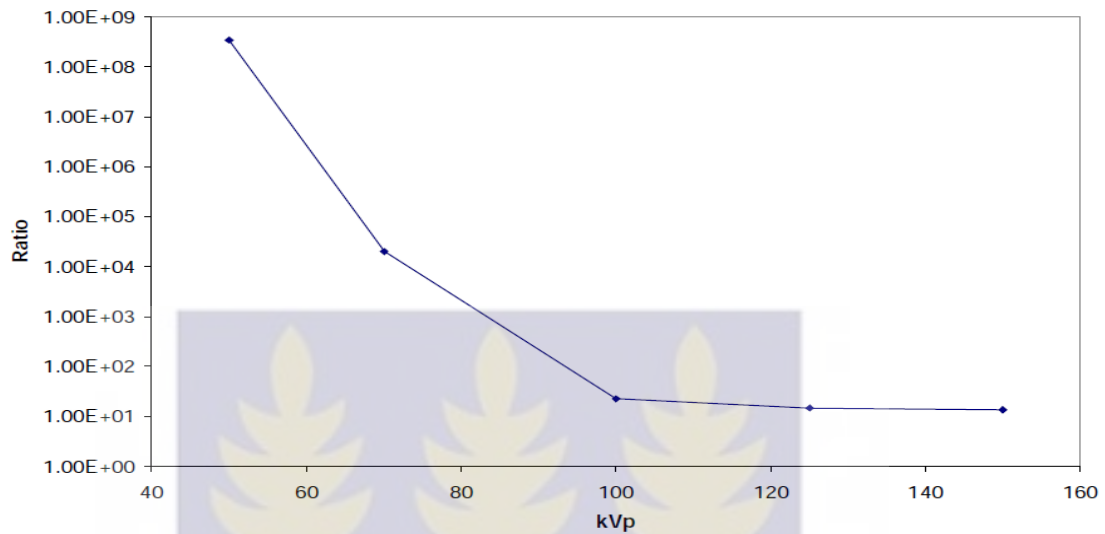
**1) Leakage radiation**

In the traditional treatment of leakage radiation, it is usual to assume that all is generated at the maximum potential of the generator/tube combination. This can lead to extremely conservative design parameters given that much radiography is performed at potentials below 100 kVp whilst leakage parameters are frequently specified at 150 kVp. Simpkin and Dixon (1998) have reworked the issue of the transmission of secondary radiation to take this fact into account. In doing so, they have demonstrated that the NCRP-49 approach to leakage radiation can result in solutions which are up to 8300 times too conservative.

The Figure 2.4 is a graph of data extracted from the work of Simpkin and Dixon and demonstrates the ratio of leakage to scatter at  $90^\circ$  for a range of accelerating potentials. The data are for a field size of  $1000 \text{ cm}^2$  and are specified at 1 metre from the sources of the scatter and leakage. The assumption is also made that protection against leakage radiation is only sufficient to ensure an air-kerma of 1 mGy/hour at 1 metre with leakage factors of 150 kVp and 3.3 mA. As has been pointed out previously the majority of x-ray tubes have more protection than this in place.

In making this conservative assumption it is evident that there will be considerably less leakage radiation than scatter at commonly used energies. Consequently, the 'add

one half value layer' approach is rejected. Instead, secondary radiation transmission curves which take into account the variation of leakage radiation are provided.



**Figure 2.4: The ratio of scatter to leakage radiation at 90 degree scattering angle.**

## 2) Scatter radiation

Scatter dose is a function of kVp, scattering angle, entrance surface dose, and the area of the x-ray beam. This principle was the basis of the standard equation used for scatter dose calculation given in [8]. This equation can be written as follow:

$$K_S = aK_U \frac{F}{400} \quad (2.4)$$

In which  $K_S$  is the scatter air-kerma at 1 m,  $K_U$  is the kerma free in air at the beam entry point,  $F \text{ cm}^2$  is the x-ray beam area at the image receptor and  $a$  is an experimentally determined constant which is a function of kV and scattering angle. Values for  $a$  given in [8] were based on data from Trout and Kelley (1972).

More recently, Williams (1996) proposed that DAP be used for scatter dose estimation. DAP meters are calibrated in terms of air-kerma product which is essentially the same as  $K_U F$  in equation (2.4). The only difference is that  $F$  is defined

at the image receptor and not at the position at which air-kerma is specified. Williams measured scatter dose as a function of angle and kV. He defined the scatter factor, S, as:

$$S = \frac{K_S}{DAP} \quad (2.5)$$

Experimental values of S (obtained from a RANDO phantom) are plotted below as a function of angle for a range of kVps in the Figure 2.4.

The S values can be approximated by the equation:

$$S = (a\theta^4 + b\theta^3 + c\theta^2 + d\theta + e) \times [(kVp - 85)f + 1] \quad (2.6)$$

For which the fitting constants are given in the Table 2.3.

**Table 2.3: Factor required for the calculation of the scatter factor S from kVp and scattering angle using equation (2.6).**

constant	value
a	$-1.042 \times 10^{-7}$
b	$2.265 \times 10^{-5}$
c	$-2.751 \times 10^{-2}$
d	$8.371 \times 10^{-2}$
e	1.578
f	$5.987 \times 10^{-3}$

These data were derived from measured values over a kV range of 50-125 kV and scattering angles between 30° and 150°.

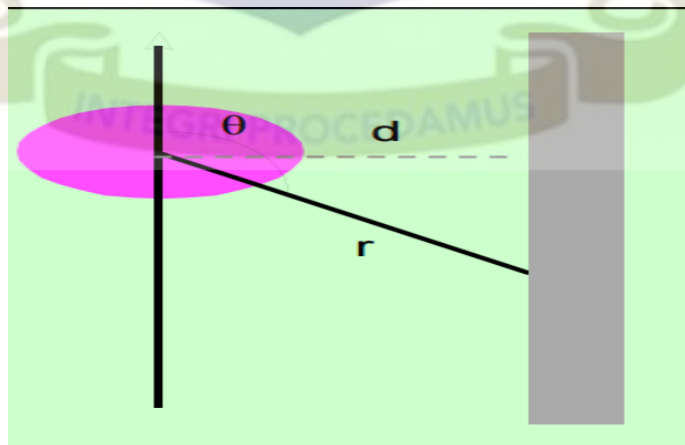
The equation is valid for scattering angle ( $\theta$ ) between 30° and 150° and tube potentials between 50 kVp and 125 kVp.

It is recommended that where possible, scatter dose is calculated from DAP using the scatter factor given by equation (2.6).

When the central ray of the X-ray beam is parallel to a shielding barrier, the angle of scatter which is directed to the point on the barrier closest to the patient is  $90^\circ$ . This is the commonest geometry in the X-ray room when considering the layout of the room walls. At greater angles, the scatter kerma increases as shown in the Figure 2.6 and the distance from the patient to the barrier also increases (see figure 2.5), which introduces a compensatory decrease in kerma owing to Inverse Square Law (ISL). Combining equation (2.6) with the ISL correction as the distance  $r$  increases with  $\theta$ , it can be shown that the maximum kerma to the barrier is at a scattering angle of  $117^\circ$ . By substituting this angle in equation (2.6) with the values of the fitting constants in the Table 2.3, it can be shown that the maximum scatter kerma ( $S_{\max}$ ) at a wall 1 m from the patient is given by:

$$S_{\max} = [(0.031 \times \text{kVp}) + 2.5] \mu\text{Gy} (\text{Gy cm}^2)^{-1} \quad (2.7)$$

For distances greater than 1 m, the ISL can be applied.



**Figure 2.5: Scatter angle  $\theta$  and distance  $r$  from a barrier which is parallel to the central ray of the X-ray beam.**

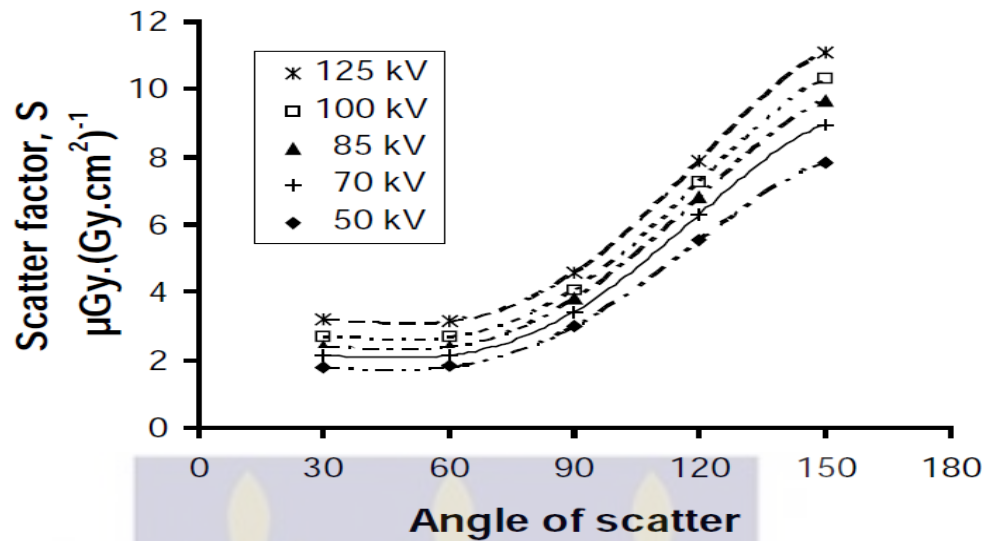
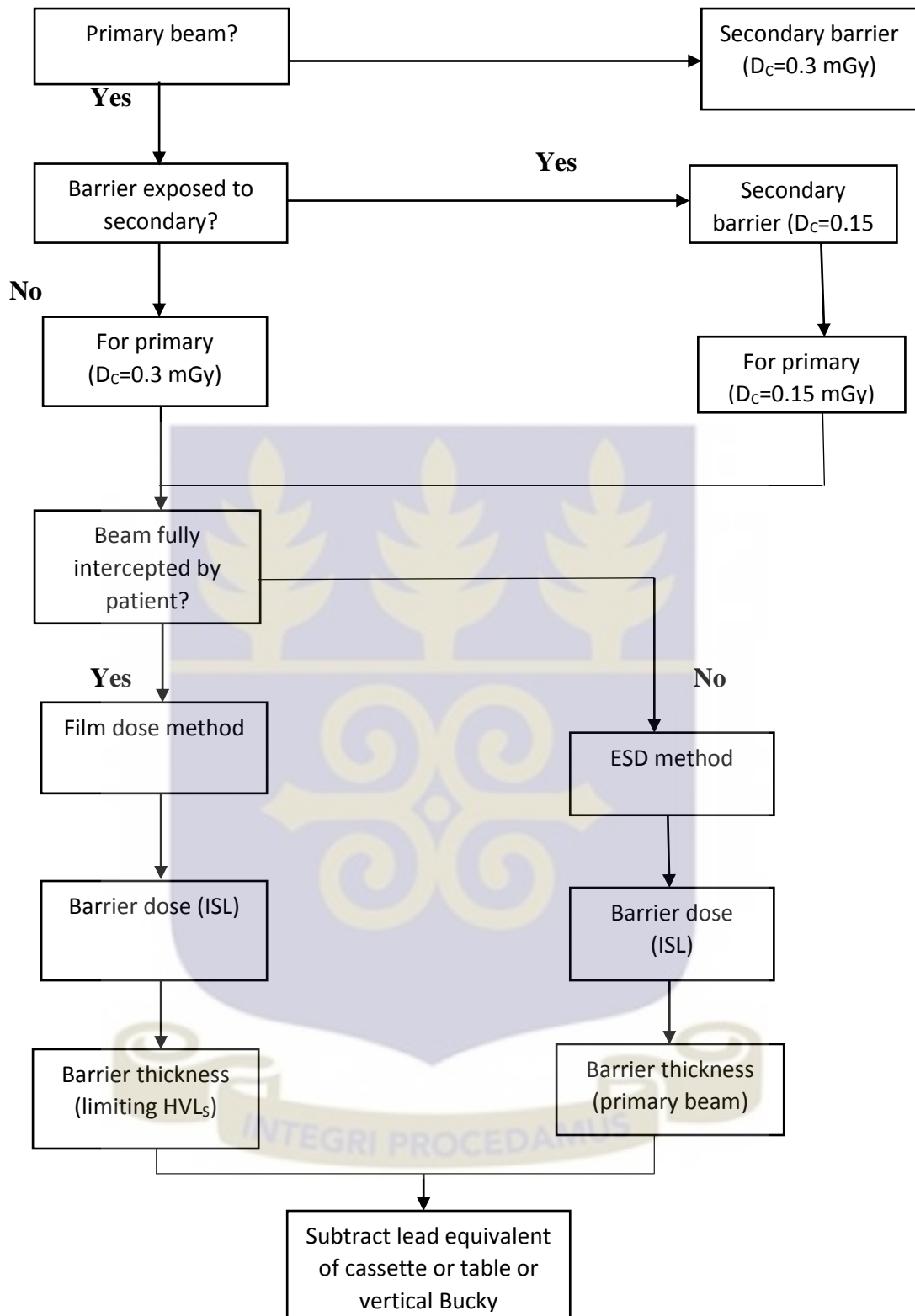


Figure 2.6: Variation of scatter with angle from Williams (1996).

### 3) Calculation involving a mix of primary and secondary radiation

On some occasions the barrier to be shielded is subject to both primary and secondary radiation. The problem becomes one of ensuring that the sum of the primary and secondary radiation transmissions through the barrier is less than 0.3 mGy.

In this situation the shielding requirement for one component does not dwarf, the BIR/IPEM working party recommends that the design criterion is halved to 0.15 mGy for each component. A calculation of the amount of shielding required for each component can then be performed and the larger value chosen as the final result. This approach is inherently conservative and will tend to overprotect when one component is considerably different to the other. Figure 2.7 shows the flow diagram indicating steps required to adopt the BIR/IPEM working party methodology.



**Figure 2.7: flow diagram indicating steps required to adopt the BIR/IPEM working party.**

### 2.1.1.2.2 Methodology adopted by the NCRP

The NCRP concepts of shielding calculation depend on:

- Shielding design goals (P),
- Distance (d) to occupied areas,
- The occupancy factor (T),
- Workload and its distribution (W),
- Use factor (U),
- Shielding materials.

#### 1. Shielding design goal

Shielding design goals are used in the design or evaluation of barriers constructed for the protection of occupationally exposed persons and members of the public. These are based on the type of area, the occupancy and distance to the occupied area. Table 2.4 presents the shielding design goal from NCRP-49 and NCRP-147.

**Table 2.4: Design goal from NCRP-49 and NCRP-147**

	<b>Controlled area</b>	<b>Uncontrolled area</b>
<b>NCRP-49 1976</b>	<b>50 mGy/y or 1 mGy/wk</b>	<b>5 mGy/y or 0.1 mGy/wk</b>
<b>NCRP-147 2004</b>	<b>5 mGy/y or 0.1 mGy/wk</b>	<b>1 mGy/y or 0.02 mGy/wk</b>
<b>Effect</b>	<b>Factor of 10 decrease</b>	<b>Factor of 5 decrease</b>

## 2. Occupancy (T)

Occupancy is a fraction of time a particular place is occupied by staff, patients or public and has to be conservative.

**Table 2.5: The NCRP-147 recommended T**

Offices, labs, pharmacies, receptionist areas, attended waiting rooms, kids' play areas, x-ray rooms, film reading areas, nursing stations, x-ray control rooms	1
Patient exam & treatment rooms	$\frac{1}{2}$
<b>Corridors</b> , patient rooms, employee lounges, staff restrooms	$\frac{1}{5}$
<b>Corridor doors</b>	$\frac{1}{8}$
Public toilets, vending areas, storage rooms, outdoor areas w/ seating, unattended waiting rooms, patient holding	$\frac{1}{20}$
Outdoors, unattended parking lots, attics, stairways, unattended elevators, janitor's closets	$\frac{1}{40}$

## 3. Workload

The workload is calculated from the knowledge of local situations. Workload can also be expressed in the form of procedures per week. The workload for a given facility is defined as the total number of milliamperes-minutes per week that the x-ray tube is in operation. The NCRP-49 had assumed that the entire workload in an installation was performed at a single kVp, 1000 mA min wk<sup>-1</sup> at 100 kVp. In NCRP-147, the average workload per patient, which may include multiple exposure due to several different radiological modalities, is called the normalized workload ( $W_{norm}$ ),

and the total workload for a given installation is the product of the normalized workload and the weekly number of patient, N.

$$W = N \times W_{norm} \quad (2.8)$$

#### 4. Use factors (for conventional diagnostic X-ray)

The use factor (U) is the fraction of the primary beam workload that is directed toward a given primary barrier. The value of U will depend on the type of radiation installation and the barrier of concern.

**Table 2.6: Primary beam use factors (U) for general radiographic room determined from the survey of clinical sites (Simpkin, 1996a).**

Barrier	Use factor (U)	Apply to workload distribution
Floor	0.89	Rad Room (floor or other barriers)
Cross-table wall	0.09	Rad Room (floor or other barriers)
Wall opposite to the cross-table wall	0.02	Rad Room (floor or other barriers)
Chest image receptor	1	Rad Room (chest-bucky)

The shielding requirements for the ceiling of a radiographic facility is determined by the secondary barrier rather than by the use factor, which is generally extremely low.

#### 5. Distances

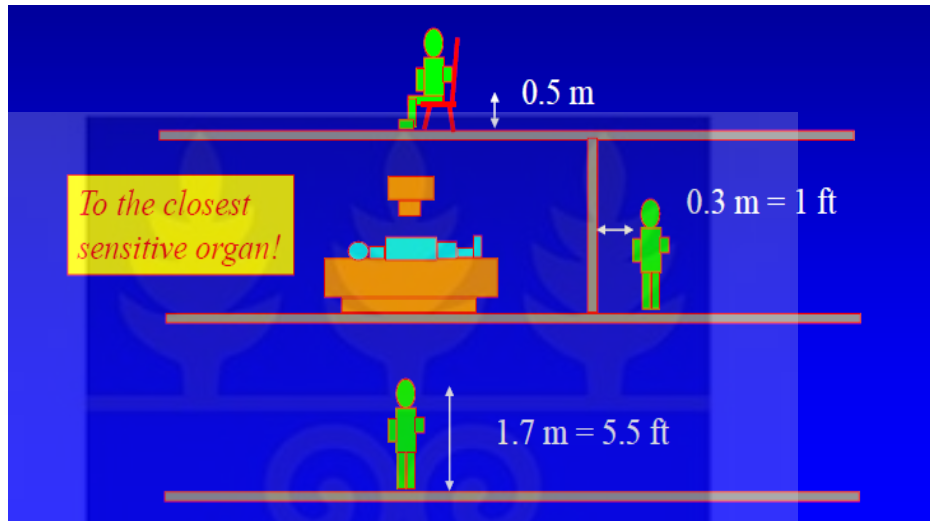
The distances measured are in metres from either the primary (dpri) or secondary (dsec) radiation source to the occupied area. NCRP Report 147 recommends the following default distances:

- for areas above the source (storey building or room above source): 0.5 m;
- for areas behind the barrier wall: 0.3 m; and

- For areas below the source: 1.7 m.

These distances are chosen because it is presumed to be closest to sensitive organs of the person who normally occupy these areas.

The Figure 2.8 below shows the occupied area where the kerma should be calculated.



**Figure 2.8: Distances in which the air kerma should be calculated**

## 6. Formula for calculation of shielding requirements

The objective of a shielding calculation is to determine the thickness of the barrier that is sufficient to reduce the air kerma in an occupied area to a value  $\leq P/T$ , the weekly shielding design goal modified by the occupancy factor for the area to be shielded, [5].

Broad beam transmission,  $B(x, m)$ , of X rays through a shielding barrier of thickness  $x$  of a given material  $m$  is defined as the ratio of the air kerma from a broad beam to an occupied area when shielded,  $k(x)$ , to that in the unshielded condition  $k(0)$ :

$$B(x) = \frac{k(x)}{k(0)} \quad (2.9)$$

Where  $k(0)$  is the unshielded air kerma rate;  $k(x)$ , shielded air kerma rate.

Transmission depends on the energies of the x rays, the thickness, the material of the shielding barrier. The transmission,  $B(x)$ , of broad X-ray beams through a variety of shielding materials in medical x ray imaging applications has been found to be well described by a mathematical model published by Archer et al.,1983 [1]. This model has the form where  $x$  is the thickness of shielding material, and  $\alpha, \beta, \gamma$  are fitting parameters:

$$B(x) = \left[ \left( 1 + \frac{\beta}{\alpha} \right) e^{\alpha\gamma x} - \frac{\beta}{\alpha} \right]^{\frac{-1}{\gamma}} \quad (2.10)$$

This equation may be solved for the thickness  $x$  as a function of transmission  $B$ .

$$x = \frac{1}{\alpha\gamma} \ln \left( \frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right) \quad (2.11)$$

#### a) NCRP-49 method

This method requires knowing the workload  $W$ , in mA-minutes per week, the use factor  $U$ , the occupancy factor  $T$  and the distance  $d$ , in metres, from the source to the occupied area. The method involve computation of an average value for the exposure per unit workload at unit distance,  $K$ , (in mGy/mA-min at 1 metre) and then using the curves to determine the thickness of lead or concrete required to reduce radiation level to the required value.

##### i. Primary protective barriers

For primary protective barriers, the value  $K$  can be calculated from the following equation:

$$K = \frac{pd^2}{WUT} \quad (2.12)$$

Where:

P = maximum permissible weekly exposure expressed in R/week or mGy/week. For controlled areas P = 0.04 R/week or 1 mGy/week; for uncontrolled area P = 0.002 R/week or 0.1 mGy/week.

d = distance in metres from the target to the primary area.

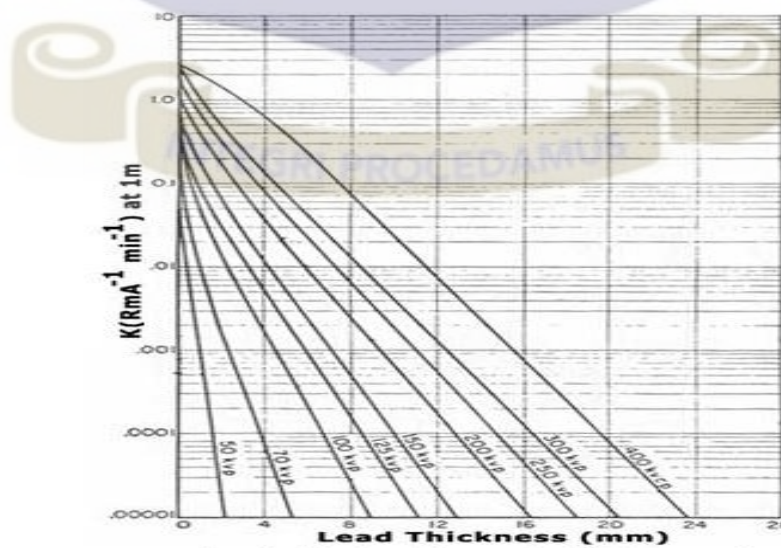
W = workload in mA-min/week

U = use factor

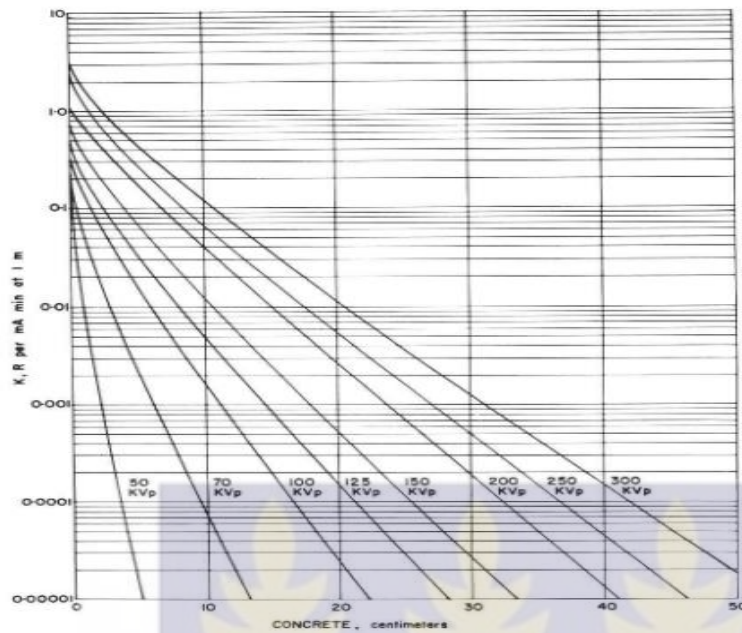
T = occupancy factor

K = exposure per unit workload at unit distance, in mGy/mA-min at 1 metre.

Figure 2.9, 2.10 represents the attenuation curve in lead and concrete of x-ray from 50 to 400 kVp.



**Figure 2.9: Attenuation in lead of x-ray from 50 to 400 kVp**



**Figure 2.10: Attenuation in concrete of x-ray generated at 50 to 300 kVp**

## ii. Secondary protective barriers

Secondary protective barriers are required to provide shielding against both leakage and scattered radiation. Since these two types of radiation are of different qualities, it is necessary to determine the barrier thickness requirements for each separately. If the computed barrier thicknesses for leakage and scatter radiation are about the same, one half-value layer should be added to the larger one to obtain the total secondary barrier thickness. If the computed leakage and scattering thicknesses differ by at least three half-value layers, the larger of the two will be adequate.

### ➤ Barrier against leakage radiation

To determine the barrier thickness required to protect against leakage radiation it is necessary to calculate the transmission factor,  $B$ , required to reduce the weekly

exposure to p. for a diagnostic- type tube housing, where the maximum allowable leakage from the housing is 0.115 R/h at 1 m.

The transmission factor is given by the following formula:

$$B = \frac{522Ip d^2}{WT} \quad (2.13)$$

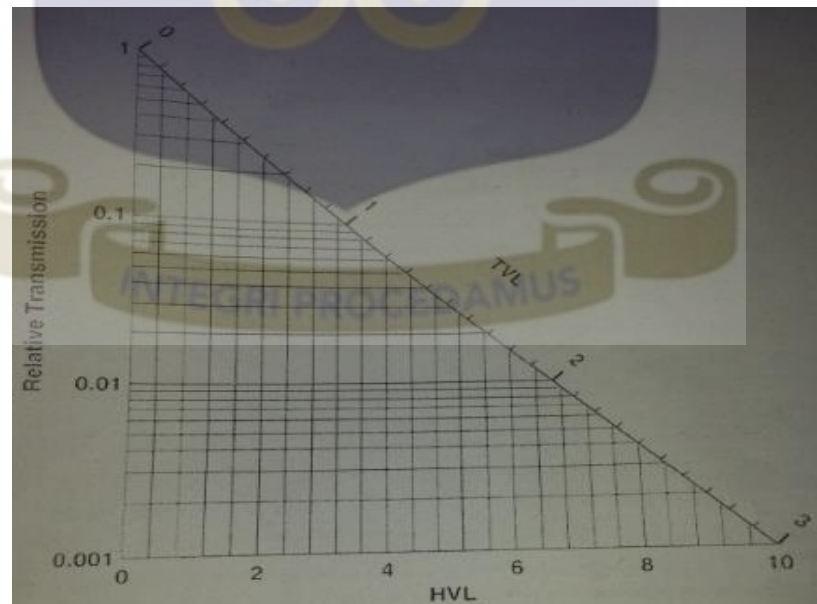
Where:

d = distance in metres from the tube housing to the secondary barrier.

I = tube current in milliamperes.

Having calculated the transmission factor, B, the barrier thickness, as a number of half-value layers or tenth-value layers, can be determined from the Figure 2.11 below.

The required barrier thickness in millimetres of lead or centimetres of concrete can be obtained from the table 2.7 below, for the appropriate energy.



**Figure 2.11: Relationship between the transmission factor B and the number of half-value layers, N, or tenth-value layers, n.**

**Table 2.7: Half-value layers and tenth-value layers for heavily filtered x-radiation under broad-beam condition**

Tube potential	Attenuation material			
	Lead (mm)		Concrete (cm)	
kVp	HVL	TVL	HVL	TVL
50	0.06	0.17	0.43	1.5
70	0.17	0.52	0.84	2.8
85	0.22	0.73	1.25	4.5
100	0.27	0.88	1.60	5.3
125	0.28	0.93	2.00	6.6
150	0.30	0.99	2.24	7.4
200	0.52	1.70	2.50	8.4
250	0.88	2.90	2.80	9.4
300	1.47	4.80	3.10	10.4

➤ **Barrier against scatter radiation**

Scattered radiation has a much lower exposure rate than that of the incident beam and usually is of lower energy. However, for X-ray equipment operating below 500 kVp it is usually assumed that the scattered X-rays have the same barrier penetrating capability as the primary beam. For X-rays generated at of less than 500 kV, the values for K can be determined from the following formula:

$$K = \frac{400pdD}{aWTF} \quad (2.14)$$

Where:

p = design goal;

d = distance in metres from the target to the scattered;

D = distance in metres from the scattered to the secondary barrier;

F = field area, in cm<sup>2</sup>;

a = ratio of scattered to incident exposure has provided in Table 2.8.

**Table 2.8: The ratio of scattered to incident exposure.**

Tube Potential kVp	Scattering angle (from central axis of beam)					
	30°	45°	60°	90°	120°	135°
50	0.0005	0.0002	0.00025	0.00035	0.0008	0.0010
70	0.00065	0.00035	0.00035	0.0005	0.0010	0.0013
85	0.0012	0.0007	0.0007	0.0009	0.0015	0.0017
100	0.0015	0.0012	0.0012	0.0013	0.0020	0.0022
125	0.0018	0.0015	0.0015	0.0015	0.0023	0.0025
150	0.0020	0.0016	0.0016	0.0016	0.0024	0.0026
200	0.0024	0.0020	0.0019	0.0019	0.0027	0.0028
250	0.0025	0.0021	0.0019	0.0019	0.0027	0.0028
300	0.0026	0.0022	0.0020	0.0019	0.0026	0.0028

#### b) NCRP-147 methods

The NCRP-147 distinguishes three models for diagnostic X-ray shielding:

- ✓ First-principle: extension to NCRP-49
- ✓ Calculation of the kerma per patient and use of transmission curves designed for particular room type.
- ✓ NT/Pd<sup>2</sup> model

#### i) First principle extension to NCRP-49

The kerma in occupied area may have contribution from:

- Primary radiation,
- Scattered radiation and
- Leakage radiation.

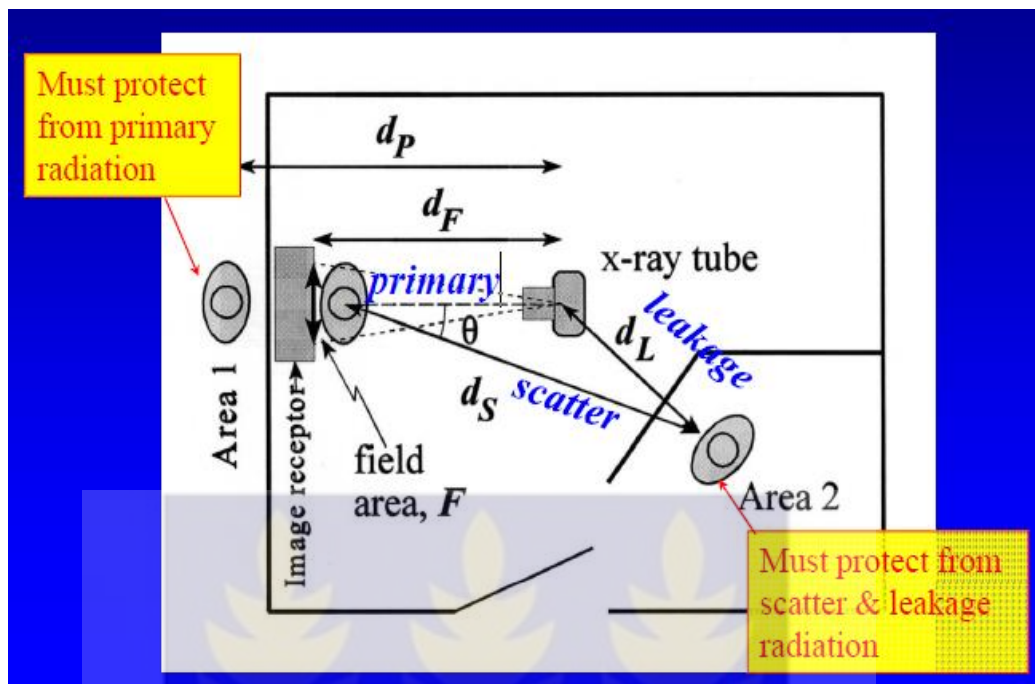


Figure 2.12: Primary, scattered and leakage radiation

- Primary beam model

The calculation of the primary beam kerma starts with the knowing of the air-kerma per unit workload at 1 m [ $K_W^1(kVp)$ ], for three phase unit (data of Archer et al. 1994).

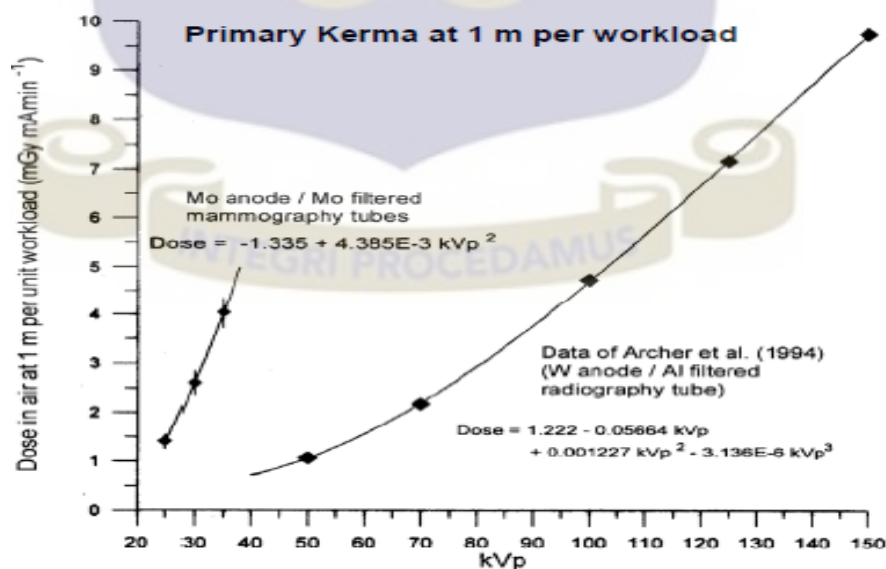


Figure 2.13: Primary beam air-kerma per unit workload at 1 m [ $K_W^1(kVp)$ ]

### Calculation of unshielded primary beam kerma

The unshielded primary air-kerma

$$K_P^1(kVp) = K_W^1(kVp)W(kVp) \quad (2.14)$$

### Calculation of the primary air-kerma due to use factor-corrected workload

At distance  $d_p$  from the focal spot of an X-ray tube, the total primary air-kerma due to use factor-corrected workload [UW (kVp)] is:

$$K_P(0, kVp) = \frac{K_W^1(kVp)UW(kVp)}{d_p^2} \quad (2.15)$$

### Calculation of the shielded air-kerma

Behind a barrier of total thickness  $x_{tot}$ , whose transmission to primary X rays at this operating potential is  $B_P(x_{tot}, kVp)$ , the shielded air-kerma is:

$$K_P(x_{tot}, kVp) = \frac{K_W^1(kVp)UW(kVp)}{d_p^2} B_P(x_{tot}, kVp) \quad (2.16)$$

For the all distribution of workloads, total kerma is:

$$K_P(x_{tot}) = \sum_{kVp} K_P(x_{tot}, kVp) = \sum_{kVp} \frac{K_W^1(kVp)UW(kVp)}{d_p^2} B_P(x_{tot}, kVp) \quad (2.17)$$

- **Scattered radiation**

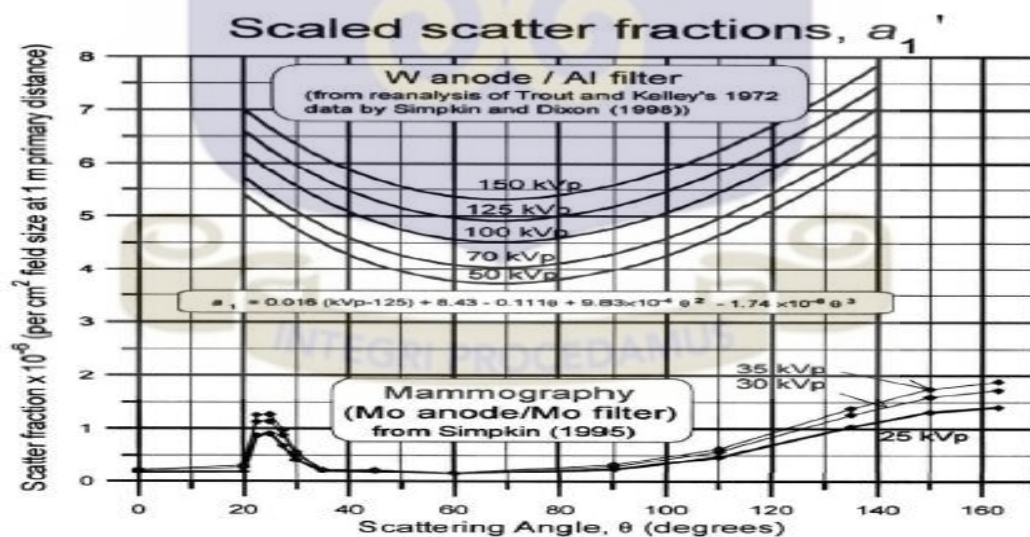
The intensity of X-rays scattered off the patient is dependent on the scattering angle  $\theta$  (defined from the direction of the centre of the primary beam to a ray pointing to the occupied area), the number of primary photons incident on the patient, the primary photon beam energy, and the location of the X-ray beam on the patient. It is assumed that the number of primary photon incident on the patient varies linearly with the X-

ray beam field size. The ratio of scattered to primary air-kerma, when divided by the primary beam field size at 1 m primary distance, defines the scatter fraction ( $a_1$ ).

The scatter fraction is given by equation 2.18.

$$a_1(\theta, kVp) = 1.6 \times 10^{-2}(kVp - 125) + 8.43 - 0.111\theta + 9.83 \times 10^{-4} \times \theta^2 - 1.74 \times 10^{-6} \times \theta^3 \quad (2.18)$$

The scatter fraction  $a_1$  is broadly distributed over a range of beam sizes with coefficients of variation on the order of 30 percent. Figure 2.14 shows  $a_1$  scaled by  $10^{-6}$  (i.e., values taken from Figure 2.14 need to be multiplied by  $10^{-6}$ ) determined from Trout and Kelley (1972) at the mean plus one standard deviation level, as a function of scattering angle and operating potential. Figure 2.14 also shows  $a_1$  for mammographic beams measured by Simpkin (1996b).



**Figure 2.14:** The scatter fraction  $a_1 \times 10^{-6}$  per  $\text{cm}^2$  of primary beam area at 1 m. [Data of Trout and Kelley (1972) reanalysed by Simpkin and Dixon (1998) for tungsten anode, aluminium-filtered beams. Data of Simpkin (1996b) for molybdenum anode, molybdenum filtered mammographic beams].

### Calculation of the scattered shielded air-kerma

The scattered shielded air-kerma is calculated using equation (2.19).

$$K_S(x, \theta) = \sum_{kVp} \frac{a'_1 \times 10^{-6} K_w(kVp) W(kVp)}{d_S^2} \frac{F}{d_F^2} B(x, kVp) \quad (2.19)$$

- Leakage radiation

The leakage air-kerma rate at 1 m from the x-ray tube operated at potential kVp and tube current  $I$  is then:

$$K_L(kVp) \propto kVp^2 I B_{housing}(kVp)$$

The unshielded leakage kerma  $K_L$  (at 1 m) at a given kVp is given by equation (2.20):

$$K_L(0, kVp) = \frac{L kVp^2 (1 - U) W(kVp) B_{housing}(kVp)}{kVp_{max}^2 I_{max} B_{housing}(kVp_{max})} \quad (2.20)$$

Applying inverse square to distance  $d_L$  from tube to shielded area and putting a barrier with transmission  $\text{Expo}(-\ln(2)x/HVL)$  between tube and area yields is.

$$K_L(0, kVp) = \frac{L kVp^2 (1 - U) W(kVp) B_{housing}(kVp)}{kVp_{max}^2 I_{max} B_{housing}(kVp_{max})} \times \frac{1}{d_L^2} \times \exp\left(\frac{-\ln(2)x}{HVL(kVp)}\right) \quad (2.21)$$

The total leakage air-kerma equal to the sum of over the operating potentials in the workload:

$$K_L(x) = \sum_{kVp} K_L(x, kVp) \quad (2.22)$$

ii) **NCRP-147 shielding model n° 2**

For each clinical workload distribution, of total workload  $W_{norm}$  per patient, for both primary and secondary barriers, NCRP-147 provided:

- ✓  $K^1$ , the kerma per patient at 1 m distance
- ✓  $B$ , the transmission of the radiation generated by this workload distribution for primary or secondary barriers.

- **Calculation of the air-kerma**

The weekly unshielded primary air-kerma [ $K_p(0)$ ] in the occupied area due to  $N$  patients examined per week is:

$$K_p(0) = \frac{K_p^1 UN}{d_p^2} \quad (2.23)$$

Where  $K_p^1$  is the unshielded primary air-kerma per patient at 1 m for each of the workload distributions and  $d_p$  is the distance (in meters) from the x-ray tube to the occupied area.

- **Calculation of the transmission**

$$B_p(x_p + x_{pre}) = \frac{Pd_{pri}^2}{NTUK^1} \quad (2.24)$$

Where  $x_p$  is the thickness of shielding material,  $x_{pre}$  is the equivalent thickness of preshielding material,  $P$  is the Maximum Permissible Dose,  $d_{pri}$  is the distance from source to the primary protected barrier,  $N$  is number of patients examined in a week,

T is the occupancy factor, U is the use factor and  $K^1$  is the unshielded primary air-kerma per patient at a distance of 1 meter.

The thickness is then:

$$x_p = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{NTUK^1}{Pd_{pri}^2} \right)^\gamma + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] - x_{pre} \quad (2.25)$$

For the secondary barrier:

The transmission is:

$$B_{secondary} = \frac{Pd_{sec}^2}{NTK_{sec}} \quad (2.26)$$

$K_{sec}$  is the unshielded secondary air-kerma

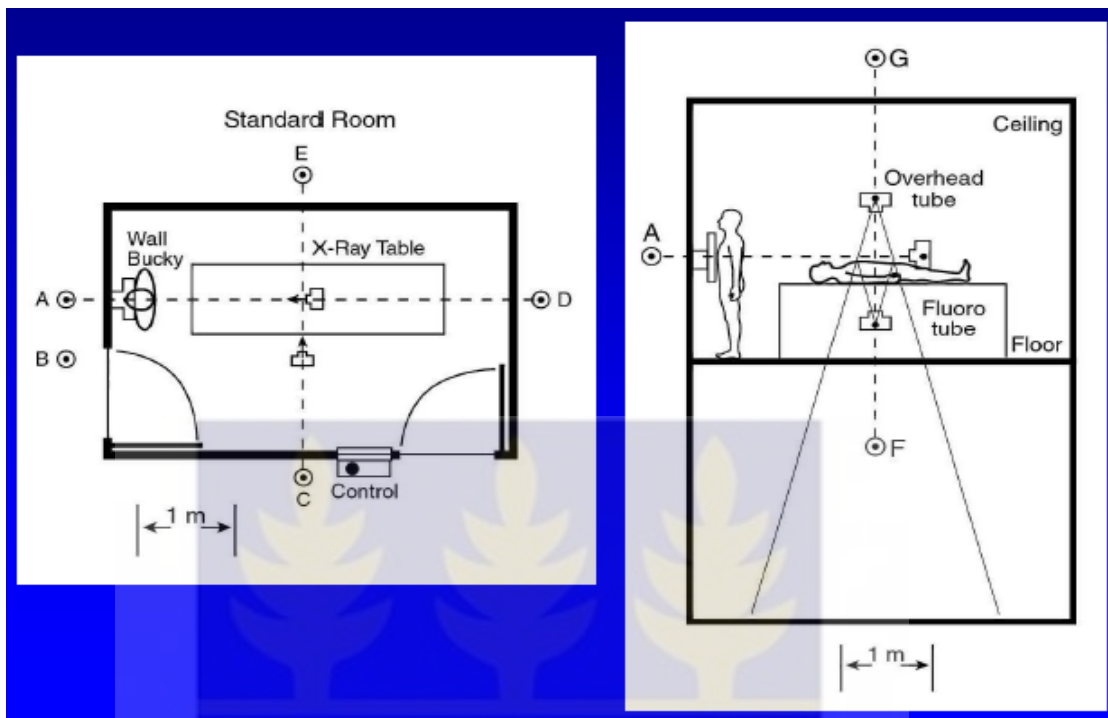
The required thickness is then:

$$x_{secondary} = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{NTK_{sec}}{Pd_{sec}^2} \right)^\gamma + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \quad (2.27)$$

### iii. NCRP-147 shielding model n° 3

Using XRAYBARR NCRP shows barrier thickness requirement calculated for representative rooms:

- Assume conservatively small room layout
- Presumes that the kinds of exposure made amongst the various X-ray tubes/position follow those observed by the AAPM TG-9 survey.



**Figure 2.15: Representative radiographic room.**

From model 2 transmission requirement is:

$$B_p(x) = \frac{Pd^2}{NTUK^1} \quad (2.28)$$

The barrier thickness requirement must scale as:

$$\frac{NT}{Pd^2}$$

- Description of the method
  - ✓ Calculate  $\frac{NT}{Pd^2}$
  - ✓ Look up the required barrier thickness on the appropriated graph for that workload distribution, barrier and barrier material.

From where is d measured?

**Table 2.9: Area from where d should be measured**

<b>Primary Barriers</b>	
Floor	Overhead radiographic tube
Chest Bucky wall	Chest tube (72`` SID)
Cross-table Lateral wall	Cross-table tube (40`` SID)
2% U wall	Centre of table
<b>Secondary Barriers</b>	
Floor	Patient on table
Chest Bucky secondary wall	Chest tube (72`` SID)
Secondary wall	Patient on table
Ceiling	Patient on table

## **2.1.2. Design and Shielding evaluation of Computed Tomography facilities**

### **2.1.2.1. Design of Computed Tomography unit**

Computed tomography (CT) employs a collimated X-ray fan-beam that is intercepted by the patient and by the detector array. Consequently, only secondary radiation is incident on protective barriers. The operating potential, typically in the range of 80 to

140 kVp, as well as the workload are much higher than for general radiography or fluoroscopy. Due to the potential for a large amount of secondary radiation, floors, walls and ceilings need special consideration. Additionally, scattered and leakage radiation levels along the axis of the patient table, the model used in the NCRP-147 assumes a conservatively safe isotropic scattered-radiation distribution. This is an important consideration if a replacement unit has a different orientation.

### 2.1.2.2. Calculation of the barriers thicknesses

- **Dose-Length Product Method**

Computed tomography is currently undergoing rapid and significant change. Several CT manufactures now display DLP values or  $CTDI_{vol}$  for a given scan series on the scanner monitor (Nagel, 2002) where:

$$\checkmark \text{ DLP (Dose-Length Product)} = CTDI_{vol} * L \quad (2.29)$$

$$\checkmark CTDI_{vol} = \frac{1/3CTDI_{100,centre} + 2/3CTDI_{100,periphery}}{p} \quad (2.30)$$

$$k_{sec}^1(\text{head}) = k_{head} \times \text{DLP}(\text{head}) \quad (2.31)$$

$$k_{sec}^1(\text{body}) = 1.2 \times k_{body} * \text{DLP}(\text{body}) \quad (2.32)$$

$k_{sec}^1$  is the secondary air-kerma at 1 m from the isocentre.

The table below gives the currently recommended default DLP values per procedure for use as a guide in planning shielding in cases where facility-specific DLP values are not available.

**Table 2.10: Recommended default DLP values per procedure provided by EC (1999)**

Procedure	DLP(mGy)
Head	1200
Chest	525
Abdomen	625
Pelvis	500
Body average(chest, abdomen or pelvis)	550

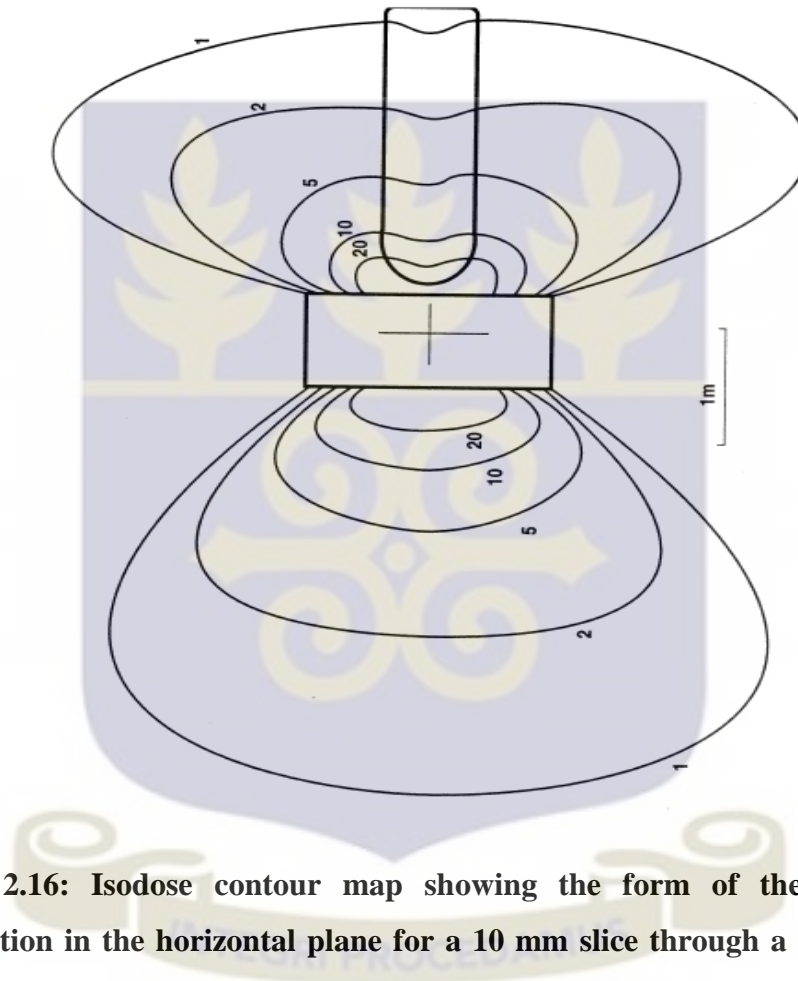
- **The isodose Map Method**

Information on scatter levels provided by manufacturers usually takes the form of isodose curves for a single slice using particular scan parameters and phantoms. Two drawings are required, one in the horizontal plane (floor plan) and one in the vertical plane (elevation). Sometimes only a single contour at a particular dose level is provided or a sequence of doses measured at a range of positions at the same distance from the isocentre according to an ISL at distances beyond the limit of dose contour plots. The decline in scatter with distance from the isocentre may be plotted for critical directions to determine the dose level at relevant boundaries.

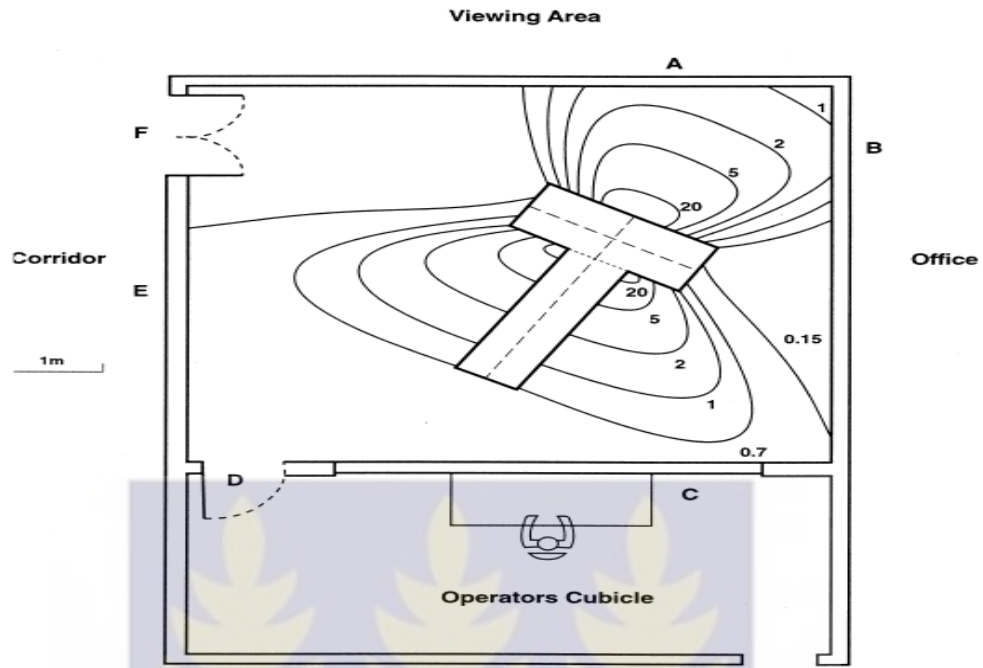
Scatter diagrams provided by X-ray companies would normally have been produced using standard PMMA phantoms representing the head (16 cm diameter) and body (32 cm diameter). Scatter from a body phantom may be 20-100% higher than that from a head phantom when the same exposure factors are used, as a result of the greater volume of tissue irradiated and the use of different filter options. Self-shielding by the body is generally not included and may reduce the dose by 50% in certain directions. However, it is not recommended that adjustments are made to

allow for this, since it will depend on body size and the scanner will be used to scan phantoms during QA tests.

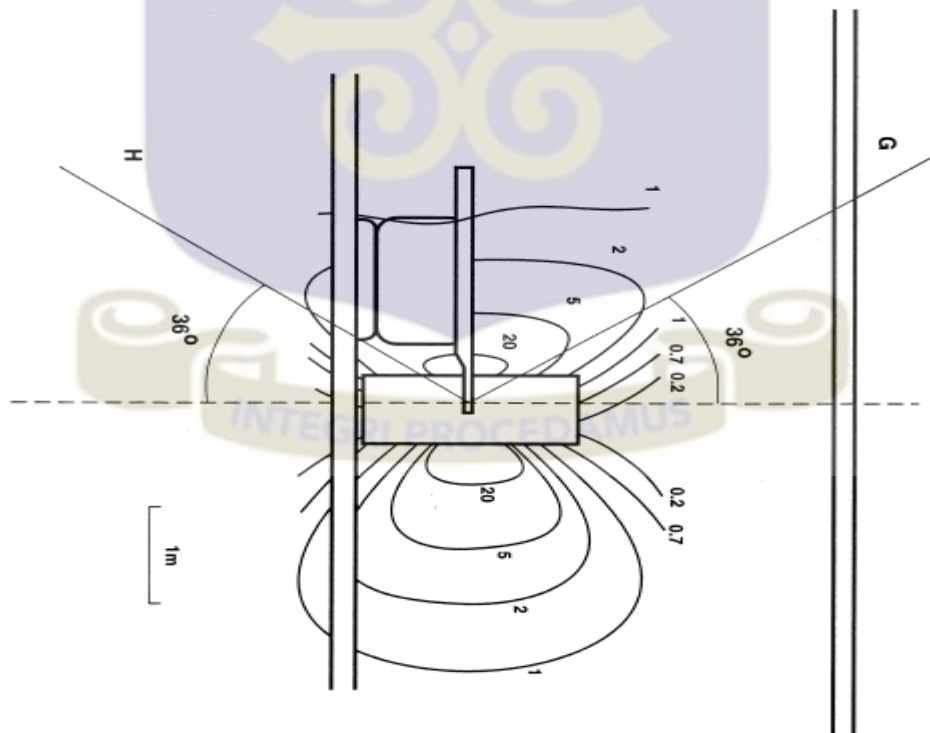
In order to estimate dose levels from scatter plots, the workload in the Department must be predicted in terms of the scan parameters used.



**Figure 2.16: Isodose contour map showing the form of the scatter dose distribution in the horizontal plane for a 10 mm slice through a head phantom using 120 kVp and 350 mAs.**



**Figure 2.17: Plan of CT room with isodose contours sketched in for a 10 mm slice using 120 kVp and 250 mAs for a phantom.**



**Figure 2.18: elevation of CT room with isodose contours sketched in for a 10 mm slice using 120 kVp and 250 mAs for a phantom.**

### 2.1.3. Design and shielding evaluation of Mammography x-ray facilities

#### 2.1.3.1 Design of Mammography unit

Mammography is radiographic imaging of the breast. Specially- designed equipment, consisting of an X-ray tube with a molybdenum, rhodium or tungsten anode and molybdenum, rhodium or aluminium filtration. X-ray mammography possesses a number of unique properties when compared to other x-ray modalities:

- The maximum energy of the primary x-ray beam is in the range 25 - 35 kV, and will typically be <30kV;
- The typical unit, with a molybdenum anode and molybdenum filter is lightly filtered (0.3 - 0.4 mm Al), giving a very low average x-ray energy;
- Equipment is designed so that the primary beam is constrained to fall within the area of the image receptor, and therefore in practice only scattered radiation needs to be considered.

#### 2.1.3.2 Shielding evaluation for Mammography

To determine the barrier thickness the following method can be used:

- ✓ Calculate  $\frac{NT}{Pd^2}$
- ✓ Look up the required barrier thickness on the graph appropriate for that workload distribution, barrier and barrier material.

## **2.2. Regulatory requirements for the design and shielding of medical x-ray facilities**

### **2.2.1. X-ray room design**

Provisions for the incorporation of safety features are best made at the facility design stage (X-ray rooms and other related rooms). The three factors relevant to dose reduction (time, distance and shielding) can be combined in the design to optimize protection. Larger rooms are preferable to allow easy access for patients on a bed trolley and to reduce exposure of the staff as well as the public, and at the same time allow for patient positioning and easy movement during the procedure, which in the case of fluoroscopy helps reduce time and exposure [9].

The following are examples of safety features:

- A protective barrier should be placed at the control console to shield staff, who should not need to wear protective clothing while at the console.
- The design of the room should be such that the X-ray beam cannot be directed at any area which is not shielded, i.e. the dose received in this area would be unacceptable.
- The X-ray room should be designed so as to avoid the direct incidence of the X-ray beam on the access doors. The doors should be made to act as a protective shield for scattered radiation and be shut when the X-ray beam is on.
- The operator needs to be able to clearly observe the patient at all times during an X-ray diagnostic procedure.
- A radiation warning sign should be posted on each entrance to an X-ray room as an indicator of radiation. A sign should also be posted to indicate that the X-ray room is a controlled area.

- A warning light should be placed at the entrance to any room where x-ray fluoroscopy or computed tomography (CT) equipment is in use. The light should be illuminated when the X-ray beam is energized.
- In rooms with a heavy workload using fluoroscopy with staff close to the patients, such as rooms for interventional procedures, it is advisable that ceiling mounted protective screens and table mounted leaded curtains be installed.

### **2.2.2. Considerations about shielding calculation**

The nominal design dose (shielding design goal) parameters in occupied areas is derived by the process of constrained optimization, i.e. selecting a source related dose constraint, with the condition that the individual doses from all relevant sources is well below the dose limits for the persons occupying the area to be shielded. Shielding barriers are calculated by the attenuation they have to provide.

The shielding thickness is obtained from the attenuation factor, which is required to reduce the dose that would be received by staff and the public if shielding were not present to a dose value that can be considered as acceptable, as a result of an optimization process, i.e. a nominal design dose derived by a process of optimization:

(a) Doses that would be received without shielding are calculated by using tabulated workload values (mAm in per week for the most relevant beam qualities, i.e. kV and filtration), tabulated 'use factors' for a given beam direction (fraction of the total amount of radiation emitted in that direction) and tabulated 'occupancy factors' (fraction of the total exposure that will actually affect individuals at a place, by virtue of the time permanence in that place). For secondary barriers, the 'use factor' is always unity, since scatter and leakage radiation is propagated in all directions all the time.

(b) Once the dose that would be received without shielding is known, it is necessary to calculate the attenuation that is necessary to reduce this dose to a design level or to a level that can be considered 'optimized protection', i.e. a dose below which additional cost and effort in shielding is not warranted by the dose being averted. This would require successive calculations to determine where this level lies. The nominal design dose in occupied areas is derived by the process of constrained optimization, i.e. selecting a source related dose constraint, with the condition that the individual doses from all relevant sources are well below the dose limits for the individuals occupying the area to be shielded. However, when using constraints for shielding calculations, consideration should be given to the remark made in ICRP Publication 33, that actual dose values to individuals are 1/10 (for equivalent dose) to 1/30 of dose values of effective dose used as shielding design parameters. This is due to a number of conservative assumptions made in the calculation. Typical conservative assumptions used in shielding design are:

- Attenuation by the patient and image receptor is usually not considered;
- Workload, Use and Occupancy factors are overestimated;
- Staff members are always in the most exposed place of the room
- Distances are the minimum possible all the time;
- Leakage radiation is the maximum all the time (corresponding to the least favourable exposure factors);
- Field size used for the calculation of scatter radiation is usually overestimated.
- The numerical value of calculated air-kerma (in mGy) is directly 'used' to compare with dose limits or constraints (mSv), which are given in terms of effective dose. However, the actual effective dose is substantially lower than the air-kerma, given the dose distribution within the body for the beam qualities used in diagnostic radiology.

## CHAPTER THREE

### 3.0. MATERIALS AND METHODS

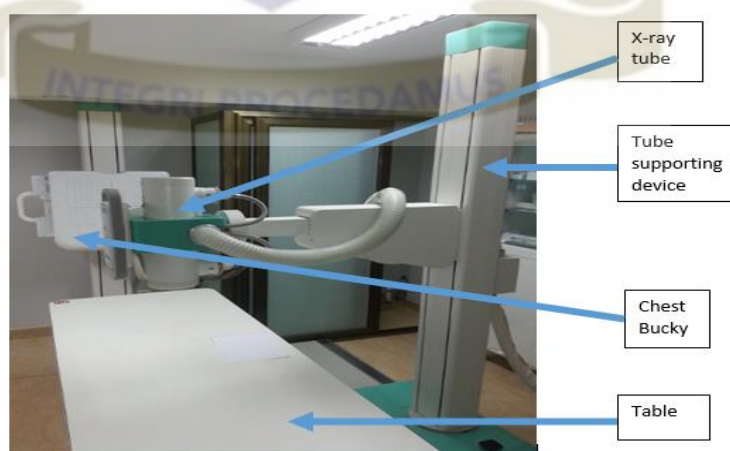
This chapter presents materials and methods used for the research work. The method used is based on the NCRP-147 methodologies and the materials include those used for the medical imaging and those used for measurements.

#### 3.1. Materials

##### 3.1.1. Equipment used for medical imaging

###### 1. Equipment used for radiography in facility A

The equipment used for radiographic imaging in the facility A is the FUJIFILM Medical solution (FDR Smart), model E7884X. The system is composed of the radiographic table, the chest Bucky, the X-ray tube (TOSHIBA), the film printer device and the control panel. The maximum selectable tube current is 500 mA and the maximum selectable tube voltage is 150 kVp. Figures 3.1, 3.2 (a), 3.2 (b), 3.3 (a) and 3.3 (b) show the Radiographic system and accessories for facility A.



**Figure 3.1: Radiographic system**



Figure 3.2 (a): The cassette reader

Figure 3.2 (b): X-ray tube

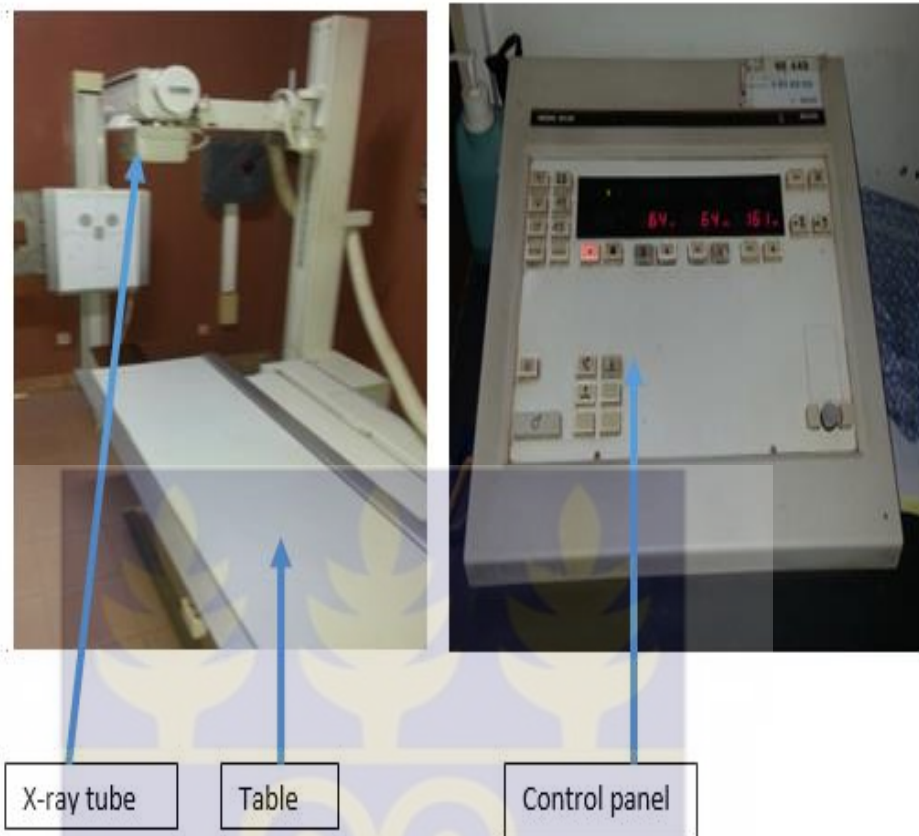


**Figure 3.3 (a): The control panel    Figure 3.3 (b): Lead glass windows**

## **2. Equipment used for radiography in facility B**

The equipment used for radiographic imaging in the facility B is PHILIPS (MEDIO 50 CP), series 65449. The system is composed of the radiographic table, the chest Bucky, the X-ray tube (PHILIPS), the film printer device and the control panel. The maximum selectable tube current is 500 mA and the maximum selectable tube voltage is 150 kVp.

Figure 3.4 (a) and (b): show the radiographic system and accessories for Facility B



**Figure 3.4 (a): The radiographic system      Figure 3.4 (b): Control panel**

### **3. Equipment used for CT scanner in facility A**

The equipment used for the CT imaging in the facility A is a product of SIEMENS, with model number 10891400 and the serial number 88020. The maximum tube voltage is 130 kVp and the maximum current is 345 mA.

After each patient scan the DLP, the kVp, the mAs are recorded in the computer.

### **4. Equipment used for CT in facility B**

The device used for CT scanner is made by General Electric, the model is BRIVO CT 325, the maximum tube voltage of the equipment is 140 kVp and the maximum current is 200 mA.

Figures 3.5 (a) and (b) show Siemens CT machine for facility A and General Electric CT machine for facility B respectively.



**Figure 3.5 (a) Siemens CT Machine    Figure 3.5 (b) General Electric CT Machine**

### **3.1.2 Equipment for measurements**

For the measurements of the different room dimensions the tape measure were used and for the measurement of the ambient dose behind each barrier a calibrated EBERLINE RO20 SI Ion Chamber: RO20UK-SI SN: 01092 was used.



**Figure 3.6: EBERLINE RO20**

### **3.1.3 Software for calculation**

Excel spreadsheet was used for each calculation. AutoCAD have been used for plan and elevation drawing of each radiography and each CT room.

## **3.2. Methods**

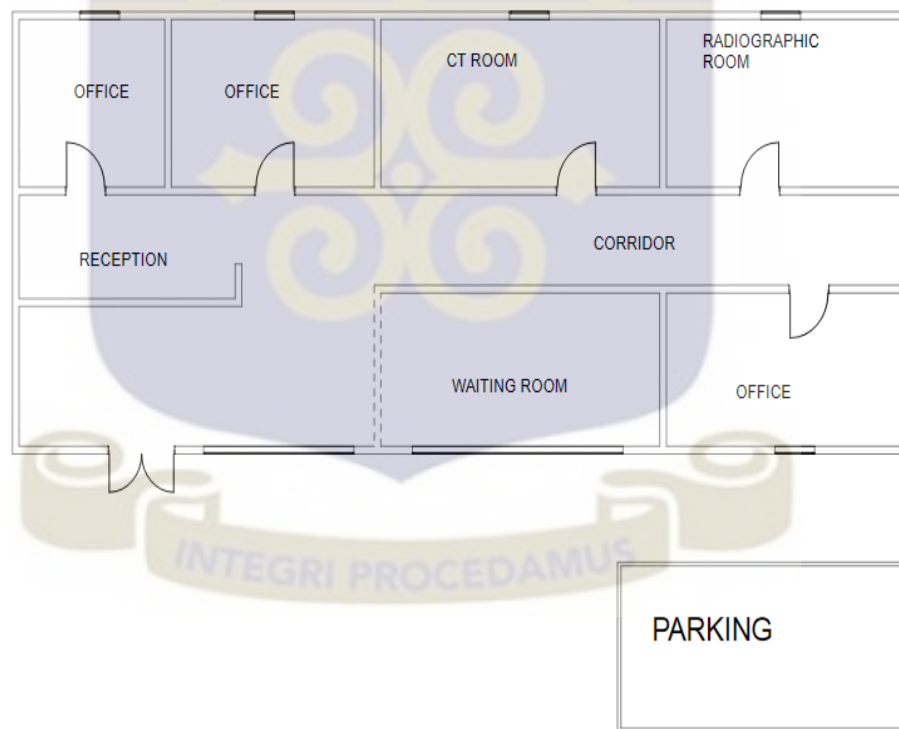
### **3.2.1. Data collection**

In this study, for each patient examination, the kVp, the mAs, the number of exposures (including repetitions), and the direction of the primary beam (chest Bucky or table) were recorded manually for three (3) months in radiography rooms in two (2) private medical imaging facilities. For facility A, a total of 440 patients was surveyed from the chest Bucky and 289 from the table, which gives a total of 729 patients. For facility B, a total of 365 patients was surveyed from the chest Bucky and 341 patients from the table, which gives a total of 706 patients. For these same facilities, the type of procedure (head or body), and the DLP were collected in CT rooms within the same period of three (3) months. A total of 293 body procedures and 190 head

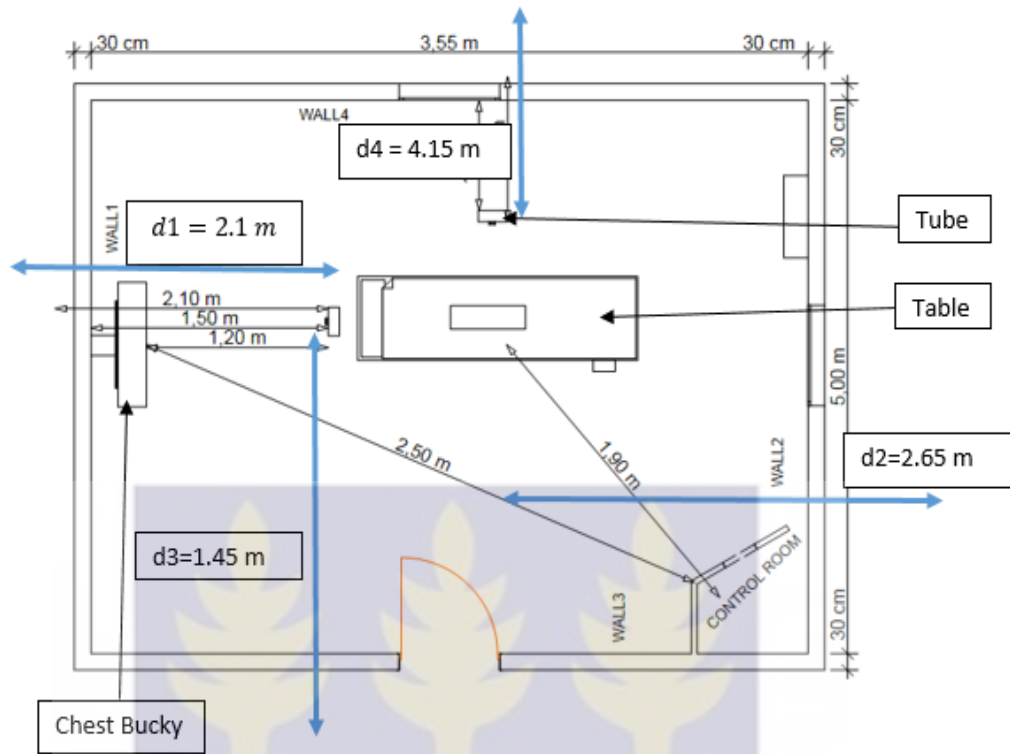
procedures were done in facility A. A total of 195 body procedures and 160 head procedures were surveyed in facility B.

### 3.2.2 Design of the radiography and CT rooms

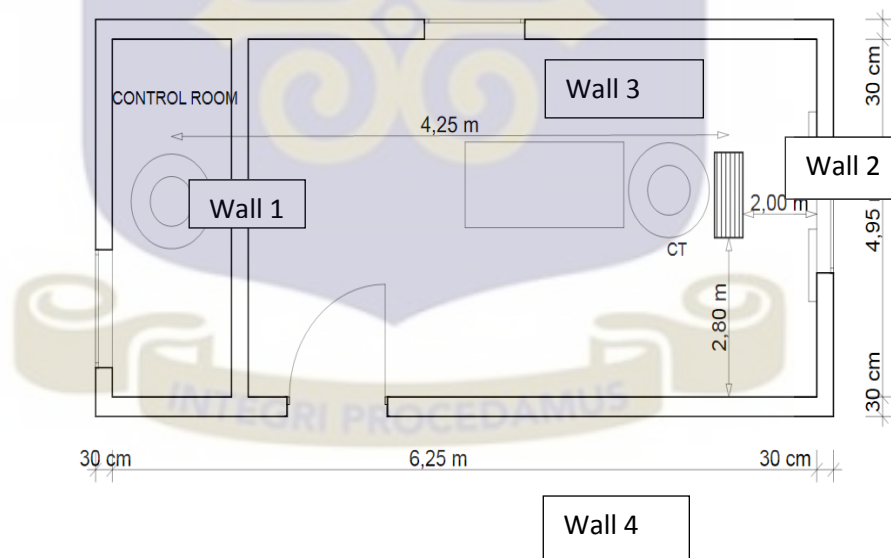
For the determination of occupancy factors and the primary and secondary distances, the elevation and plan drawing were done. These drawings were done by using a tape measure for the measurements of the dimensions of the rooms, the distances from the focal spot to critical points, walls thicknesses etc. After that a computer programme named AutoCAD was used to design each type of drawing, shown in Figures 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14.



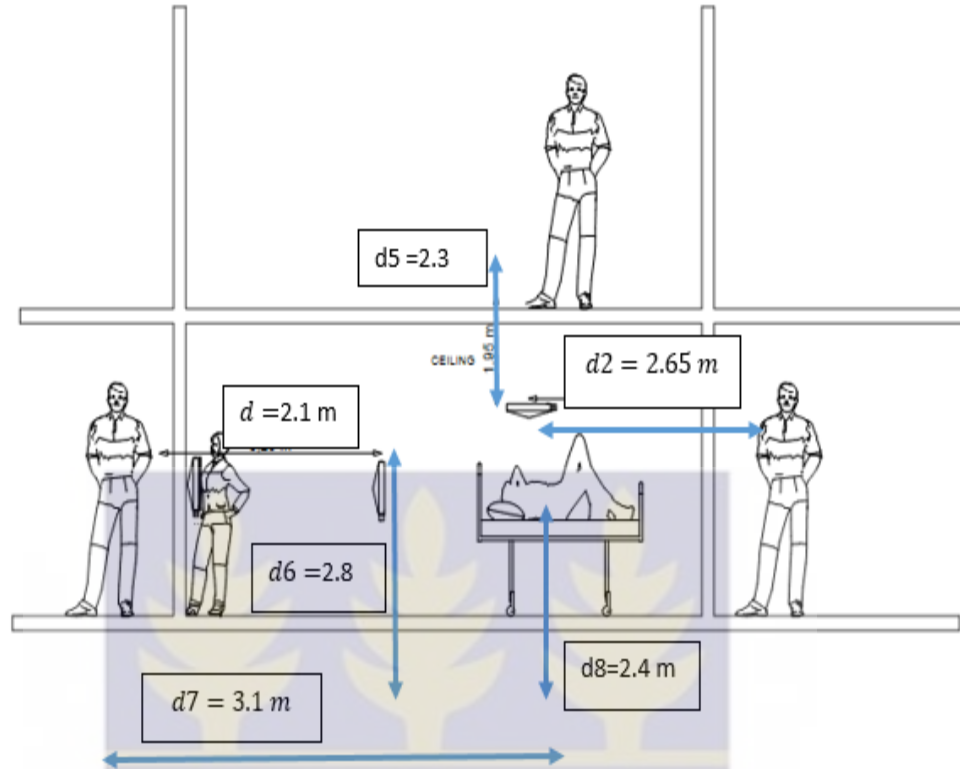
**Figure 3.7: General view plan of facility A**



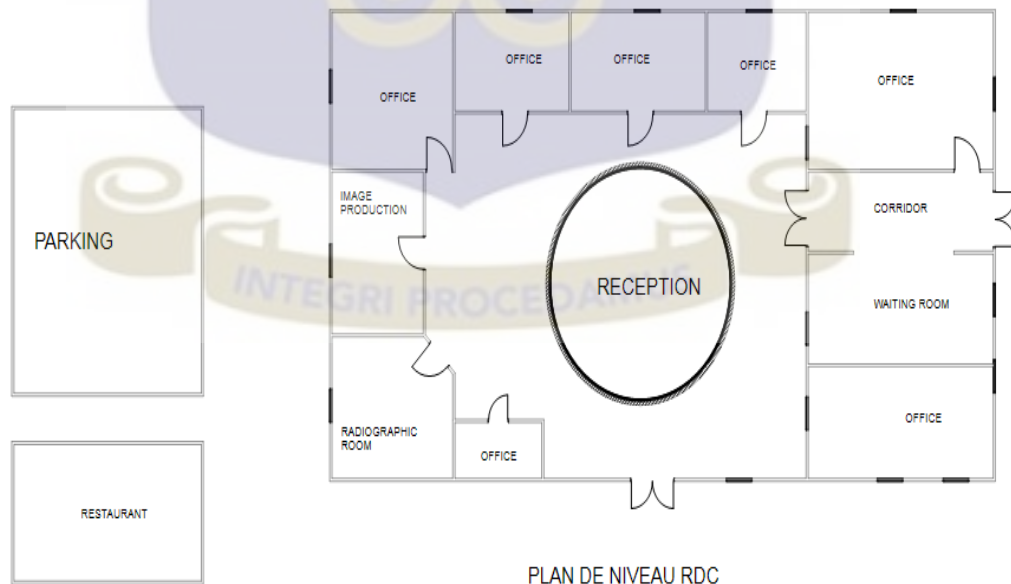
**Figure 3.8: Plan drawing of the radiographic room for facility A**



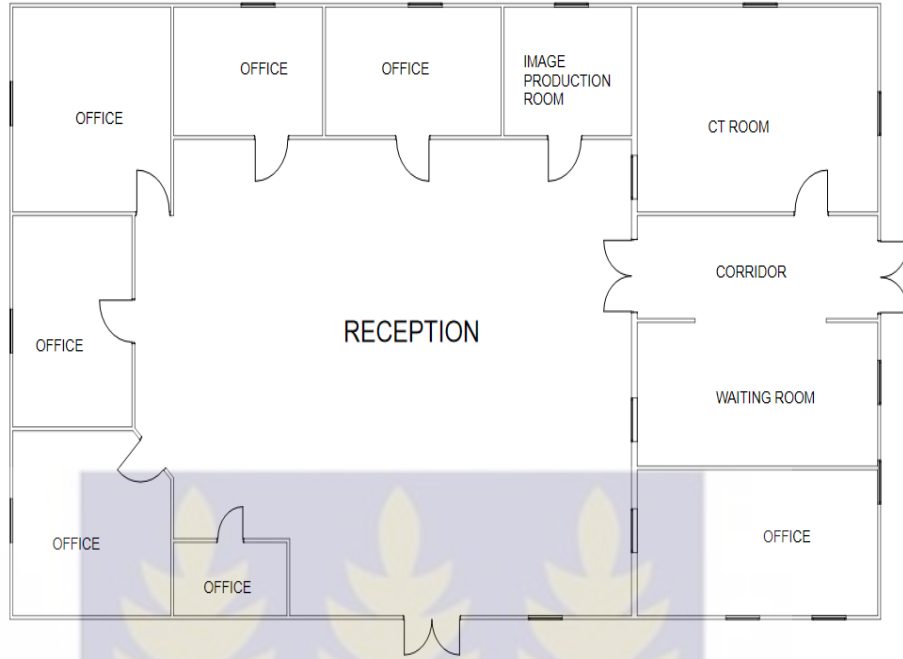
**Figure 3.9: Plan drawing of CT room for facility A**



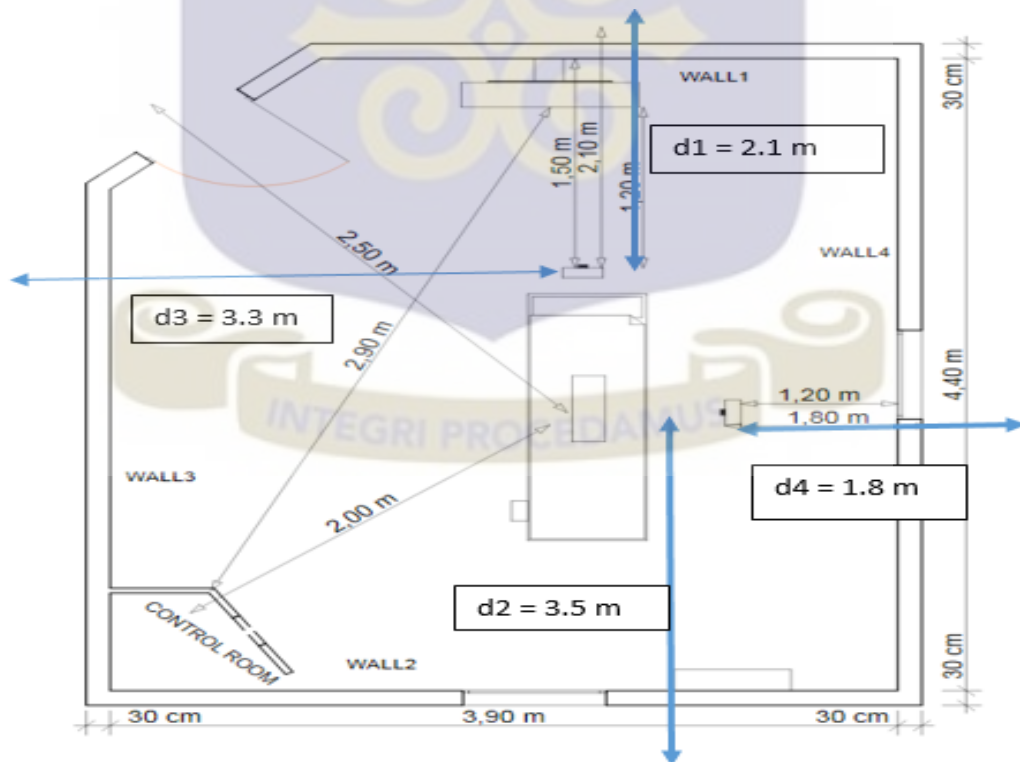
**Figure 3.10: Elevation drawing of the radiographic room for facility A**



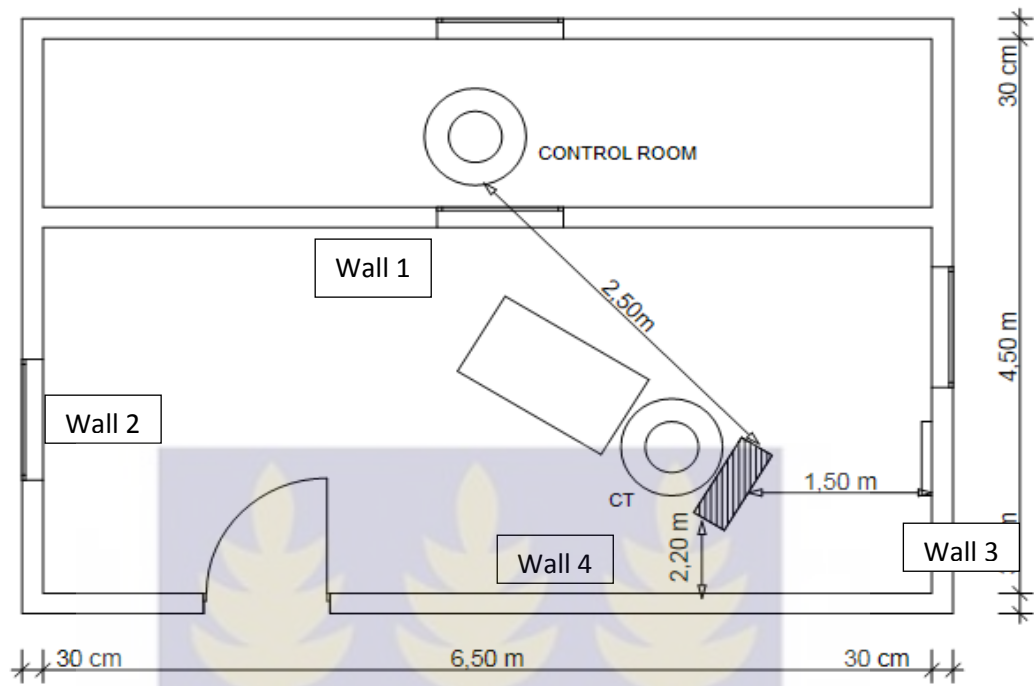
**Figure 3.11: General view plan for the floor of facility B**



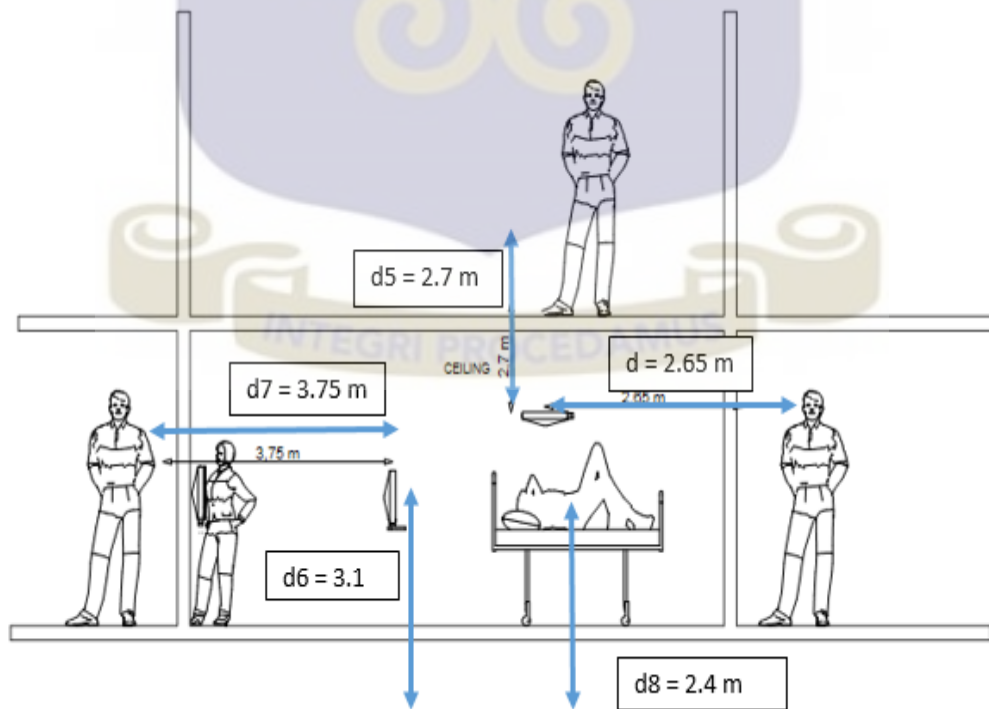
**Figure 3.12: General view plan for the first floor of facility B**



**Figure 3.13: Plan drawing of the radiographic room for facility B**



**Figure 3.14: Plan drawing of CT room for facility B**



**Figure 3.15: Elevation drawing of the radiographic room for facility B**

### 3.2.3. Determination of the kVp distribution of workload normalized per patient for each radiography installation

For each radiography installation, the kVp, the mAs, the number of exposures (including repetitions) were collected manually. The mAs was accumulated in a 5 kVp wide bin. For the conservative safe assumption, the higher value of the kVp was considered for each bin due to the direct proportion that exists between the kVp and the kerma. The average workload for each kVp bin was calculated and the sum of the workload for each kVp distribution provided the normalized workload per patient for the radiography installation.

### 3.2.4 Determination of the use factor for the Floor and for the chest Bucky

To determine the use factor for each direction (floor and wall supporting the chest Bucky), the total normalized workload per patient of the room was determined first, and for each direction the use factor was obtained by dividing the normalized workload per patient for the radiography installation by the total normalized workload per patient of the radiography room. The Table 3.1 provides the use factor for each Radiography (Rad) Room at facility A and B.

**Table 3.1: Use factor for each Rad Room.**

Rad Room	Facility A		Facility B	
	Normalized workload	Use factor	Normalized workload	Use factor
Floor	0.96	<b>0.43</b>	1.14	<b>0.68</b>
Chest Bucky wall	1.25	<b>0.57</b>	0.53	<b>0.32</b>

### 3.2.5. Determination of distances from the source of primary and secondary radiation to the location of the maximally-exposed individual beyond primary and secondary barriers for each radiographic room

For the wall1 (chest Bucky), the primary distance was determined by measuring the distance between the focal spot of the X-ray tube and the wall supporting the chest assembly, by adding the existing wall thickness, plus 0.3 m (distance from the wall to the occupied area).

For the floor, the primary distance was determined by measuring the distance between the focal spot of the X-ray tube and the floor, by adding the existing floor thickness, plus (HC-1.7m) where HC is the height of the radiographic room in meter.

Secondary barriers consist of the wall1 (chest Bucky), wall2, wall3, wall4, floor, the plate glass, and the ceiling. For each of these barriers, two component have to be taken into account; scattered and leakage radiation. Assuming  $d_s$  as the distance from the source of scattered radiation to the secondary barrier,  $d_l$  the distance from the tube to the secondary barrier. For the conservative safe assumption,  $d_{sec} = \text{minimum}(d_s, d_l)$  was considered (confer figures 3.8, 3.10, 3.13, 3.14 and 3.15).

**Table 3.2: Distances from the source of primary radiation to the location of the maximally-exposed individual beyond primary barriers.**

Facility	A	B
Floor	3.1 m	3.1 m
Chest Bucky	2.1 m	2.1 m

**Table 3.3: Distances from the source of secondary radiation to the location of the maximally-exposed individual beyond secondary barriers and the corresponding occupancy factors.**

Facility	A		B	
	$d_{sec}$ (m)	occupancy	$d_{sec}$ (m)	occupancy
Floor	2.40	1.00	2.40	1.00
Chest Bucky (wall1) (d1)	3.10	1.00	3.1	1.00
Room opposite to chest Bucky (wall2) (d2)	2.65	1.00	3.50	1.00
Cross-table lateral wall (wall4) (d4)	4.15	0.25	1.80	0.25
Secondary wall opposite to the cross-table lateral wall (wall3) (d3)	2.05	0.20	3.30	1.00
Ceiling (d5)	2.30	1.00	2.30	1.00
Control wall	1.90	1.00	2.00	1.00

**3.2.6. Determination of distances from the isocentre of the gantry to the location of the maximally-exposed individual beyond secondary barriers for CT room in Facilities A and B**

The distances determined are shown in Table 3.4

**Table 3.4: Distances from the isocentre of the gantry to the location of the maximally-exposed individual beyond secondary barriers for CT room in facilities A and B**

Facility	A		B	
	$d_{sec}$ (m)	occupancy	$d_{sec}$ (m)	Occupancy
Wall 1	4.85	1.000	2.90	1.000
Wall 2	2.60	1.000	5.60	0.500
Wall 3	2.75	0.200	2.10	0.125
Wall 4	3.40	0.200	2.80	0.200

### 3.2.7 Calculation of the unshielded primary Air Kerma

#### 3.2.7.1 Calculation of the primary beam Air kerma at unit workload at 1 m

$[K_W^1(kVp)]$

The primary Air kerma per unit workload for each kVp were calculated from the equation 3.1, Archer et al. (1994).

$$[K_W^1(kVp)] = 1.222 - 5.664 \times 10^{-2} \times kVp + 1.227 \times 10^{-3} \times kVp^2 - 3.136 \times 10^{-6} \times kVp^3 \quad (3.1)$$

#### 3.2.7.2 Calculation of the primary air-kerma at 1 m for each kVp

The equation 3.2 was used to calculate the primary air-kerma at 1 m for each kVp distribution.

$$K_P^1(kVp) = [K_W^1(kVp)] \times W(kVp) \quad (3.2)$$

The unshielded primary air-kerma values at 1 m from the tube were calculated using equation 3.3.

$$K_p^1 = \sum_{kVp} [K_W^1(kVp)] \times W(kVp) \quad (3.3)$$

### 3.2.8. Calculation of the primary barriers thicknesses

For the barrier supporting the chest Bucky, the image receptor is available to provide attenuation of the primary beam before it strikes the structural barrier. The barrier thickness is then calculated using equation 3.4.

$$x_p = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{NTUK_p^1}{Pd_{pri}^2} \right)^\gamma + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] - x_{pre} \quad (3.4)$$

Where:

- N is the number of patient examined in a week,
- T is the occupancy factor,
- $d_{pri}^2$  is the distance from the focal spot of the r-ray tube to the primary barrier,
- P is the shielding design goal,
- $\alpha, \beta, \gamma$  are fitting parameters,
- $x_{pre}$  is the image receptor preshielding thickness.

Table 3.5 shows the minimum equivalent value of  $x_{pre}$  that may be used with any of the workload distribution.

**Table 3.5: Equivalent thickness of primary beam preshielding ( $x_{pre}$ )**

Application	$x_{pre}$ (in mm)		
	Lead	Concrete	Steel
Image receptor in radiographic table or wall-mounted cassette holder (attenuation by grid, cassette, and image-receptor supporting structures)	0.85	72	7
Cross-table lateral (attenuation by grid and cassette only)	0.30	30	2

For the floor some examination are done with attenuation device and other without attenuation. For the conservatively safe assumption it was assumed that all examination were done without preshielding material. Then the thickness is given through the equation 3.5.

$$x_p = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{NTUK_p^1}{Pd_{pri}^2} \right)^{\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \quad (3.5)$$

Table 3.6 shows fitting parameters for transmission of broad primary X-ray beam.

**Table 3.6: Fitting parameters for transmission of broad primary X-ray beam**

Workload distribution	Lead			Concrete		
	$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$	$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$
Rad Room (chest Bucky)	2.264	13.08	0.56	0.03552	0.1177	0.6007
Rad Room (floor)	2.651	16.56	0.4585	0.03994	0.1448	0.4231

### 3.2.9. Calculation of the unshielded secondary air-kerma

#### 3.2.9.1. Calculation of the unshielded scatter air-kerma

The unshielded scattered air-kerma at a given scatter angle  $\theta$  at a given kVp and at a scattered radiation distance  $d_s = 1$  from the patient is calculated using the equation

3.6.

$$K_S(\theta, kVp) = \frac{K_P^1(kVp) \times a_1(\theta, kVp) \times (1-U) \times 10^{-6} \times F}{d_F^2} \quad (3.6)$$

Where:

- $a_1(\theta, kVp)$  is the scatter fraction for a given scatter angle  $\theta$  and a given kVp
- $F$  is the primary beam field size measured in  $\text{cm}^2$
- $d_F^2$  is the Source-to-image-receptor distance (SID)

The scatter fraction were calculated using the equation 3.7. This equation is a work of Trout and Kelley (1972) and reanalysed by Simpkin and Dixon (1998) for tungsten anode, aluminium-filtered beams.

$$\alpha_1(\theta, kVp) = 1.6 \times 10^{-2}(kVp - 125) + 8.43 - 0.111 \times \theta + 9.83 \times 10^{-4} \times \theta^2 - 1.74 \times 10^{-6} \times \theta^3 \quad (3.7)$$

The total unshielded scattered air-kerma is the sum over the operating potentials (equation 3.8).

$$K_S(\theta) = \sum_{kVp} \frac{K_P^1(kVp) \times \alpha_1(\theta, kVp) \times (1-U) \times 10^{-6} \times F}{d_F^2} \quad (3.8)$$

### 3.2.9.2. Calculation of the unshielded leakage air-kerma

The air-kerma from leakage radiation was estimated by assuming that the leakage radiation intensity with no housing is equal to that of the primary beam. For each of the two facilities under study, the chosen leakage technique factors was 150 kVp and 3.3 mA. Then the tube housing thickness required to reduce leakage radiation to the regulatory limit (0.876 mGy h<sup>-1</sup>) is 2.32 mm of lead. For each kVp interval the unshielded air-kerma is attenuated by the transmission factor  $e^{-2.32\alpha}$  and summed to obtain the unshielded leakage air-kerma. The values of the attenuation coefficient ( $\alpha$ ) are provided in the Table 3.7.

The unshielded leakage air-kerma at a given kVp and at leakage radiation distance

$d_L = 1$  m from the X-ray tube was calculated using the equation 3.9.

$$K_L(kVp) = K_P^1(kVp) \times e^{-2.32\alpha} \quad (3.9)$$

The unshielded leakage air Kerma at leakage radiation distance  $d_L = 1$  from the X-ray tube was obtained by summing  $K_L(kVp)$  for each kVp range (Equation 3.10).

$$K_L = \sum_{kVp} K_P^1(kVp) \times e^{-2.32\alpha} \quad (3.10)$$

### 3.2.9.3. Calculation of the total unshielded secondary air-kerma

The total unshielded secondary air-kerma was obtained using equations 3.8 and 3.10 to obtain equation 3.11.

$$K_{sec}^1 = K_S(\theta) + K_L \quad (3.11)$$

### 3.2.10. Calculation of secondary barriers thicknesses

Having the secondary unshielded air-kerma at 1 m, the secondary barriers thicknesses was calculated through the equation 3.12.

$$x_{secondary} = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{NTK_{sec}^1}{Pd_{sec}^2} \right)^\gamma + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \quad (3.12)$$

Where  $d_{sec} = \text{minimum}(d_S, d_L)$

Table 3.7 provides the fitting parameters for transmission of broad secondary X-ray beam.

**Table 3.7: Fitting parameters for transmission of broad secondary X-ray beam. (Data of Simpkin, 1996).**

Workload distribution	Lead			Concrete		
	$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$	$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$
Chest-bucky	2.256	13.8	0.8837	0.03560	0.1079	0.7705
Floor	2.513	17.34	0.4994	0.03920	0.1464	0.4486
all barriers	2.298	17.38	0.6193	0.03610	0.1433	0.56

### 3.2.11. Calculation of the average DLP for head and for the Body for the facility

#### A and for the facility B

For each of these two facilities, patients' examinations were divided into two:

- Head scan and
- Body scan.

For each examination, the total DLP, the type of examination (head or body) was provided on the computer screen. For each type of examination, the DLPs recorded for three months were summed and divided by the total number of patients to obtain the average DLP.

### 3.2.12. Calculation of the unshielded secondary air-kerma for facility A and facility B

The unshielded secondary air-kerma at 1 meter from the isocentre for head and for body were determined using the following equations:

$$\bullet \quad k_{sec}^1(\text{head}) = k_{\text{head}} \times \text{DLP}(\text{head}) \quad (3.13)$$

$$\bullet \quad k_{sec}^1(\text{body}) = 1.2 \times k_{\text{body}} * \text{DLP}(\text{body}) \quad (3.14)$$

Where:

$$\checkmark \quad k_{\text{head}} = 9 \times 10^{-5} \text{ 1/cm.}$$

$$\checkmark \quad k_{\text{body}} = 3 \times 10^{-4} \text{ 1/cm.}$$

The total unshielded weekly secondary air Kerma at 1 meter of the isocentre was calculated through equation 3.15

$$k_{sec}^1 = [n_b \times k_{sec}^1(\text{body}) + n_h \times k_{sec}^1(\text{head})] \quad (3.15)$$

Where:

✓  $n_b$  is the weekly number of patients undergoing body scan and

✓  $n_h$  is the weekly number of patients undergoing head scan.

### 3.2.13. Calculation of secondary barriers thicknesses for facility A and for facility B

The secondary barriers thicknesses was calculated through equation 3.16

$$x = \frac{1}{\alpha\gamma} \ln \left[ \frac{\left( \frac{TK_{sec}^1}{Pd_{sec}^2} \right)^\gamma + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \quad (3.16)$$

**Table 3.8: Fitting parameters for transmission of secondary X-ray beam for 120 kVp (data of Simpkin, 1996).**

Lead			concrete		
$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$	$\alpha(\text{mm}^{-1})$	$\beta(\text{mm}^{-1})$	$\gamma$
2.246	5.73	0.547	0.0383	0.0142	0.658

### 3.2.14. Dose rate measurements

The dose rate was measured using a filled 20 litres water gallon as a phantom. The gallon was located at 1 meter from the source of the radiography rooms (Figure 3.14 and 3.15). The parameters (kVp, mAs) for the most frequently used procedure were used. The measurements were done with the gallon on the table and with the gallon on the chest-Bucky. The maximum dose rate was considered for each barrier. For CT rooms the filled water gallon was placed on the table and the parameters (kVp, mAs) for the most frequently used procedure was chosen.





**Figure 3.16: Water gallon on the table at 1 m of the source**



**Figure 3.17: Water gallon on the chest-Bucky at 1 m of the source.**

## CHAPTER FOUR

### 4.0. RESULTS AND DISCUSSIONS

This chapter presents the results on estimated normalized workload per patient for each radiographic installation (floor and chest Bucky), the corresponding primary air-kerma at 1 meter from the X-ray tube, scattered and leakage air-kerma at 1 meter from the source of scatter and leakage radiation, primary and secondary barriers thicknesses. For Computer Tomography facilities the chapter presents the average DLP values for the head and for the body as well as secondary barriers thicknesses for facilities A and B. It also discusses the results found from this work and inter-comparison with corresponding values from NCRP-147 and American Association of Physicists in Medicine (AAPM-TG9).

#### 4.1. Results

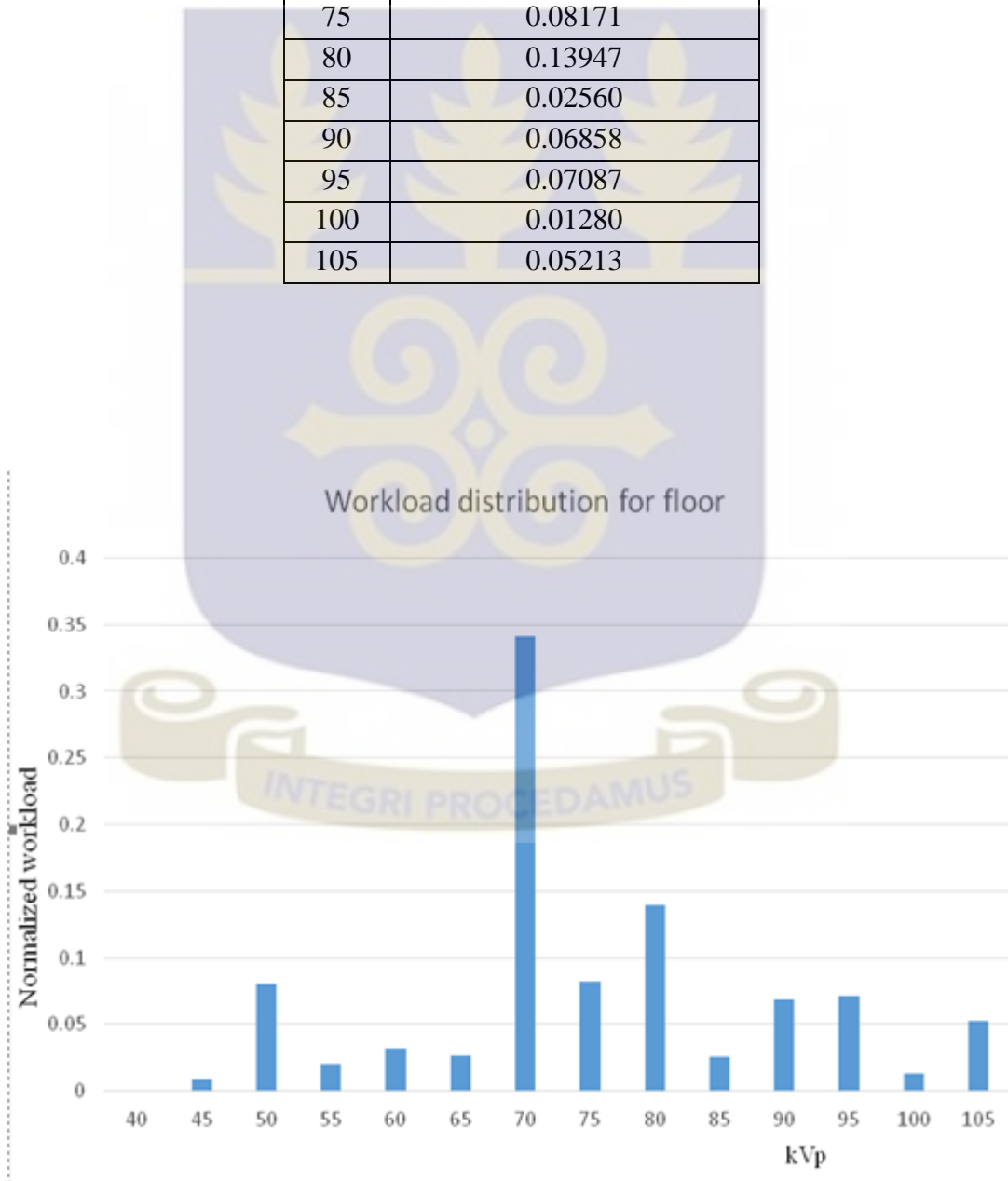
##### 4.1.1. The kVp distribution of workload and normalized workload per patient

###### 4.1.1.1. The kVp distribution of workload

The kVp distribution of workload shows ranges of kVp the most used for examination within each radiographic installation. Tables 4.1, 4.2, 4.3, and 4.4, and Figures 4.1, 4.2, 4.3 and 4.4 present the workload distribution, and the workload distribution plot for floor and for the chest-bucky for facility A and facility B.

**Table 4.1: Workload distribution for the floor in facility A.**

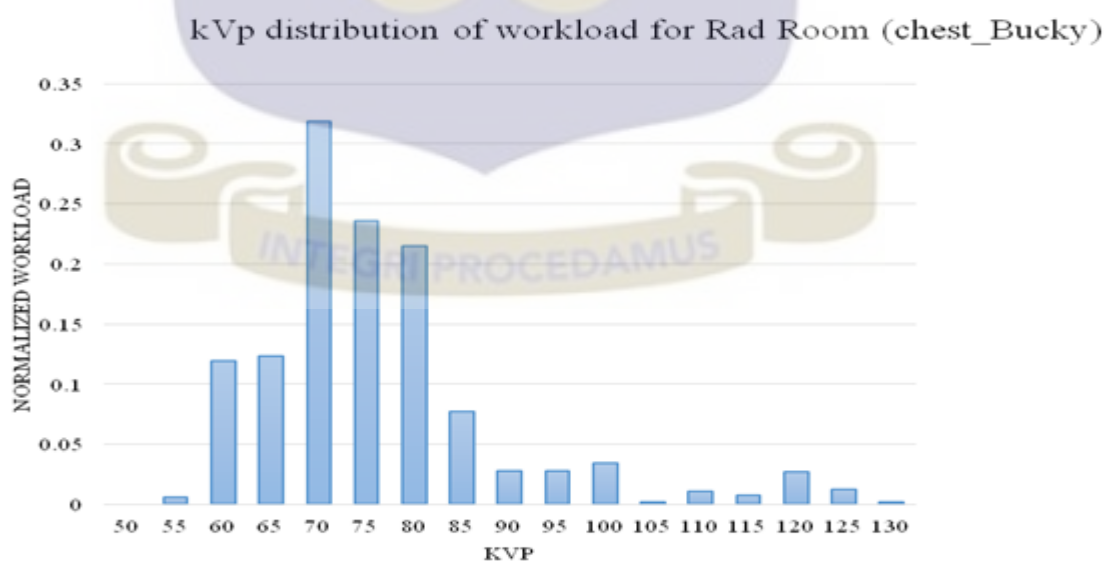
kVp	Workload per kVp (W(kVp))
40	0.00000
45	0.00878
50	0.08035
55	0.02055
60	0.03195
65	0.02652
70	0.34095
75	0.08171
80	0.13947
85	0.02560
90	0.06858
95	0.07087
100	0.01280
105	0.05213



**Figure 4.1: The kVp distribution of workload plot for floor (facility A).**

**Table 4.2: Workload distribution for the chest-Bucky in facility A.**

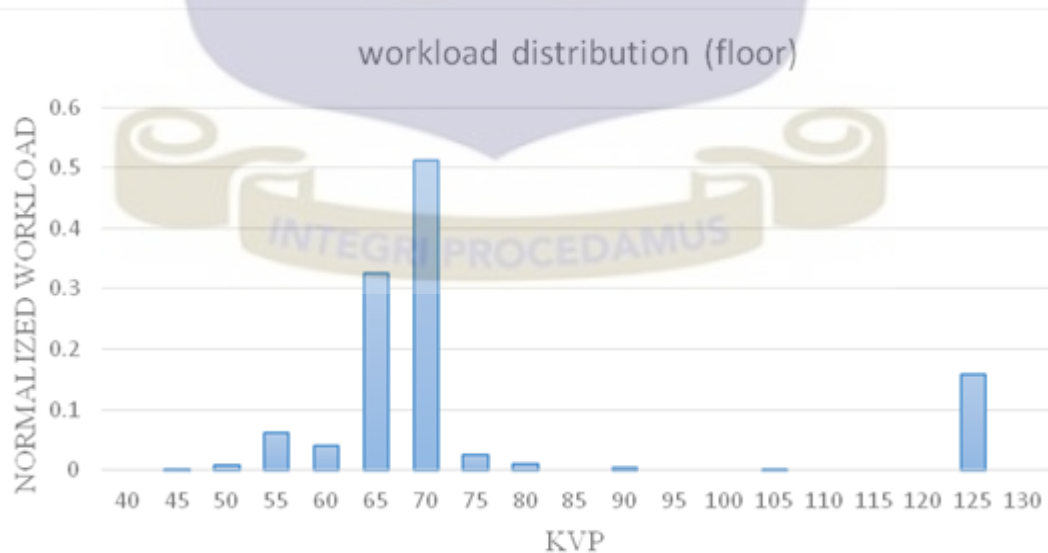
kVp	Workload per kVp (W(kVp))
50	0.00000
55	0.00557
60	0.11950
65	0.12361
70	0.31837
75	0.23557
80	0.21463
85	0.07749
90	0.02805
95	0.02802
100	0.03456
105	0.00195
110	0.01044
115	0.00787
120	0.02666
125	0.01237
130	0.00179
135	0.00000



**Figure 4.2: The kVp distribution of workload plot for chest Bucky (facility A)**

**Table 4.3: Workload distribution for floor in facility B.**

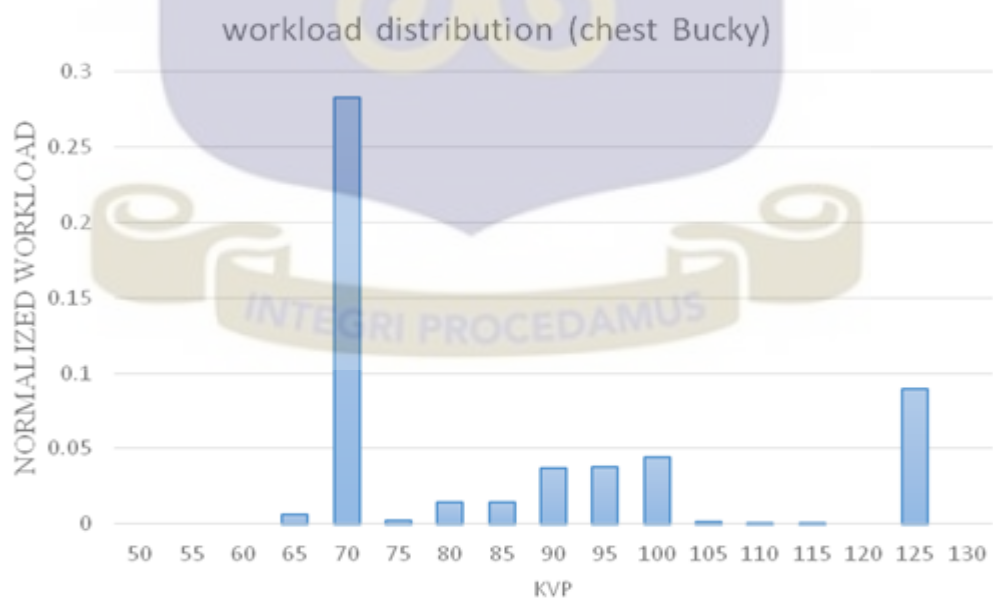
kVp	Workload kVp (W(kVp))
40	0.00000
45	0.00030
50	0.00828
55	0.06135
60	0.03886
65	0.32459
70	0.51168
75	0.02497
80	0.00906
85	0.00000
90	0.00406
95	0.00000
100	0.00000
105	0.00047
110	0.00000
115	0.00000
120	0.00000
125	0.15911
130	0.00000



**Figure 4.3: The kVp distribution of workload plot for floor (facility B)**

**Table 4.4: Workload distribution for the chest-Bucky in facility A**

kVp	Workload kVp (W(kVp))
50	0.00000
55	0.00000
60	0.00000
65	0.00665
70	0.28290
75	0.00259
80	0.01480
85	0.01473
90	0.03666
95	0.03753
100	0.04423
105	0.00155
110	0.00106
115	0.00094
120	0.00000
125	0.08923
130	0.00000



**Figure 4.4: The kVp distribution of workload plot for chest Bucky (facility B).**

#### 4.1.1.2. The total normalized workload per patient

Table 4.5 presents the normalised workload per patient for each radiography installation (in mA min patient<sup>-1</sup>) for facility A and B, and standard values provided by the NCRP-147.

**Table 4.5: Total normalized workload per patient.**

Workload distribution	W <sub>norm</sub> (mA min patient <sup>-1</sup> )	W <sub>norm</sub> (mA min patient <sup>-1</sup> )	W <sub>norm</sub> (mA min patient <sup>-1</sup> )
	For facility A	For facility B	For NCRP-147
Floor	0.96	1.14	1.90
Chest Bucky	1.25	0.53	0.60
All barriers	2.21	1.67	2.50

Table 4.5 shows that the normalized workload per patient for all barriers in facility A is lower than those for standard values from NCRP-147 but the normalized workload per patient for the chest-bucky is higher than those from standard. For facility B the normalized workload for the floor, for the chest-bucky and for all barrier are lower than those from the NCRP-147.

#### 4.1.2. Unshielded primary air-kerma at 1 meter of the focal spot

Table 4.6 shows unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the floor for facility A.

**Table 4.6: Unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the floor for facility A.**

kVp	Workload kVp (W(kVp))	Unshielded primary air-kerma per unit workload at 1 m per kVp ( $K_w^1(kVp)$ )	Unshielded primary air-kerma 1 m per kVp ( $K_p^1(kVp)$ )
40	0.00000	0.71889	0.00000
45	0.00878	0.87210	0.00766
50	0.08035	1.06550	0.08562
55	0.02055	1.29672	0.02665
60	0.03195	1.56342	0.04995
65	0.02652	1.86325	0.04941
70	0.34095	2.19385	0.74801
75	0.08171	2.55287	0.20859
80	0.13947	2.93796	0.40976
85	0.02560	3.34677	0.08569
90	0.06858	3.77695	0.25905
95	0.07087	4.22614	0.29952
100	0.01280	4.69200	0.06007
105	0.05212	5.17216	0.26960
<b>Unshielded primary air-kerma per patient at 1 m (<math>K_p^1</math> mGy patient<sup>-1</sup>)</b>			<b>2.55962</b>

Table 4.7 shows unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the chest-Bucky for facility A.

**Table 4.7: Unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the chest-Bucky for facility A.**

kVp	Workload kVp (W(kVp))	Unshielded primary air- kerma per unit workload at 1 m per kVp ( $K_w^1(kVp)$ )	Unshielded primary air-kerma 1 m per kVp ( $K_p^1(kVp)$ )
50	0.00000	1.06550	0.00000
55	0.00557	1.29672	0.00723
60	0.11950	1.56342	0.18683
65	0.12362	1.86325	0.23033
70	0.31837	2.19385	0.69845
75	0.23557	2.55287	0.60139
80	0.21463	2.93797	0.63058
85	0.07749	3.34678	0.25934
90	0.02805	3.77696	0.10595
95	0.02802	4.22615	0.11843
100	0.03456	4.69200	0.16219
105	0.00195	5.17216	0.01008
110	0.01044	5.66428	0.05915
115	0.00788	6.16601	0.04858
120	0.02667	6.67499	0.17802
125	0.01237	7.18887	0.08893
130	0.00179	7.70530	0.01385
135	0.00000	8.22193	0.00000
<b>Unshielded primary air-kerma per patient at 1 m (<math>K_p^1</math> mGy patient<sup>-1</sup>)</b>			<b>3.39937</b>

Table 4.8 shows unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the floor for facility B.

**Table 4.8: Unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the floor for facility B.**

kVp	Workload kVp (W(kVp))	Unshielded primary air Kerma per unit workload at 1 m per kVp ( $K_w^1(kVp)$ )	Unshielded primary air Kerma 1 m per kVp ( $K_p^1(kVp)$ )
40	0.00000	0.71889	0.00000
45	0.00030	0.87210	0.00026
50	0.00829	1.06550	0.00883
55	0.06135	1.29672	0.07956
60	0.03886	1.56342	0.06075
65	0.32459	1.86325	0.60481
70	0.51168	2.19385	1.12256
75	0.02497	2.55287	0.06376
80	0.00906	2.93796	0.02663
85	0.00000	3.34678	0.00000
90	0.00406	3.77695	0.01534
95	0.00000	4.22614	0.00000
100	0.00000	4.69200	0.00000
105	0.00047	5.17216	0.00244
110	0.00000	5.66428	0.00000
115	0.00000	6.16601	0.00000
120	0.00000	6.67499	0.00000
125	0.15911	7.18887	1.14384
130	0.00000	7.70531	0.00000
<b>Unshielded primary air-kerma per patient at 1 m (<math>K_p^1</math> mGy patient<sup>-1</sup>)</b>			<b>3.12878</b>

Table 4.9 shows unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the chest-Bucky for facility B.

**Table 4.9: Unshielded primary air-kerma per patient at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for the chest-Bucky for facility B.**

<b>kVp</b>	<b>Workload kVp (W(kVp))</b>	<b>Unshielded primary air- kerma per unit workload at 1 m per kVp (<math>K_w^1</math>(kVp))</b>	<b>Unshielded primary air- kerma 1 m per kVp (<math>K_p^1</math>(kVp))</b>
50	0.00000	1.06550	0.00000
55	0.00000	1.29672	0.00000
60	0.00000	1.56342	0.00000
65	0.00666	1.86325	0.01240
70	0.28291	2.19385	0.62066
75	0.00259	2.55287	0.00663
80	0.01480	2.93797	0.04349
85	0.01473	3.34678	0.04930
90	0.03666	3.77696	0.13847
95	0.03753	4.22615	0.15863
100	0.04424	4.69200	0.20757
105	0.00156	5.17216	0.00806
110	0.00106	5.66428	0.00602
115	0.00095	6.16601	0.00582
120	0.00000	6.67499	0.00000
125	0.08923	7.18887	0.64150
130	0.00000	7.70531	0.00000
<b>Unshielded primary air-kerma per patient at 1 m (<math>K_p^1</math> mGy patient<sup>-1</sup>)</b>			<b>1.89855</b>

Table 4.10 presents the unshielded primary air-kerma at 1 meter ( $K_p^1$  mGy patient<sup>-1</sup>) for each of the radiographic installation for facility A and facility B compared with standard values from NCRP-147.

**Table 4.10: Unshielded primary air-kerma at 1 meter for each of the radiography installation for facility A and facility B compared with standard values from NCRP-147.**

Workload distribution	$K_p^1$ (mGy patient <sup>-1</sup> ) Facility A	$K_p^1$ (mGy patient <sup>-1</sup> ) Facility B	$K_p^1$ (mGy patient <sup>-1</sup> ) NCRP-147
Floor	2.56	3.13	5.20
Chest Bucky	3.40	1.90	2.30

From Table 4.10, the unshielded primary air-kerma at 1 meter from the tube for the chest-bucky for facility A is greater than the standard value but the one for the floor is less than the standard value. For facility B, the unshielded primary air-kerma at 1 meter from the tube for the floor and for the chest-bucky are lower than those from the standard. From Table 4.5 and Table 4.10 we can see that the higher the normalized workload, the higher the unshielded primary air-kerma at 1 meter from the tube.

#### 4.1.3 Scattered air-kerma at 1 meter of the source of scatter

For the conservative safe assumption the scattered air-kerma have been calculated for 90 degree scatter and for 135 degree scatter.

Table 4.11 presents the scatter air-kerma (mGy) at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the floor of the facility A.

**Table 4.11: Scatter air-kerma (mGy) at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the floor of the facility A.**

kVp	Unshielded primary air Kerma 1 m per kVp ( $K_p^1(kVp)$ )	a1(90, kVp)	a1(135, kVp)	Ks (90, kVp)	Ks(135, kVp)
40	0.00000	3.77384	5.71912	0.00000	0.00000
45	0.00766	3.85384	5.79912	0.00002	0.00003
50	0.08562	3.93384	5.87912	0.00028	0.00043
55	0.02665	4.01384	5.95912	0.00009	0.00013
60	0.04995	4.09384	6.03912	0.00017	0.00026
65	0.04941	4.17384	6.11912	0.00017	0.00026
70	0.74801	4.25384	6.19912	0.00273	0.00397
75	0.20859	4.33384	6.27912	0.00077	0.00112
80	0.40976	4.41384	6.35912	0.00155	0.00223
85	0.08569	4.49384	6.43912	0.00033	0.00047
90	0.25905	4.57384	6.51912	0.00102	0.00145
95	0.29952	4.65384	6.59912	0.00119	0.00169
100	0.06007	4.73384	6.67912	0.00024	0.00034
105	0.26960	4.81384	6.75912	0.00111	0.00156

By summing the scatter air-kerma for each kVp interval we obtain the scatter air-kerma for the floor of the facility A.

**Table 4.12: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for the floor of the facility A.**

Side-scatter (90) (mGy patient <sup>-1</sup> )	Forward/backward-scatter (135) (mGy patient <sup>-1</sup> )
<b>0.00970</b>	<b>0.01400</b>

Table 4.13 shows the scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the chest-Bucky of the facility A.

**Table 4.13: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each interval for the chest-Bucky of the facility A.**

kVp	Unshielded primary air-kerma 1 m per kVp ( $K_p^1(kVp)$ )	a1(90, kVp)	a1(135, kVp)	Ks (90, kVp)	Ks(135, kVp)
50	0.00000	3.93384	5.87912	0.00000	0.00000
55	0.00723	4.01384	5.95912	0.00001	0.00001
60	0.18683	4.09384	6.03912	0.00034	0.00050
65	0.23032	4.17384	6.11912	0.00043	0.00063
70	0.69845	4.25384	6.19912	0.00133	0.00195
75	0.60139	4.33384	6.27912	0.00117	0.00169
80	0.63058	4.41384	6.35912	0.00125	0.00180
85	0.25934	4.49384	6.43912	0.00052	0.00075
90	0.10595	4.57384	6.51912	0.00021	0.00031
95	0.11843	4.65384	6.59912	0.00024	0.00035
100	0.16219	4.73384	6.67912	0.00034	0.00049
105	0.01008	4.81384	6.75912	0.00002	0.00003
110	0.05915	4.89384	6.83912	0.00013	0.00018
115	0.04857	4.97384	6.91912	0.00011	0.00015
120	0.17802	5.05384	6.99912	0.00040	0.00056
125	0.08893	5.13384	7.07912	0.00021	0.00028
130	0.01385	5.21384	7.15912	0.00001	0.00004
135	0.00000	5.29384	7.23912	0.00000	0.00000

By summing the scatter air-kerma for each kVp interval we obtain the scatter air-kerma for the chest-bucky of the facility A.

**Table 4.14: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for the chest-bucky of the facility A.**

Side-scatter (90) (mGy patient <sup>-1</sup> )	Forward/backward-scatter (135) (mGy patient <sup>-1</sup> )
0.00680	0.00980

Table 4.15 shows the scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the floor of the facility B.

**Table 4.15: scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each interval for the floor of the facility B.**

kVp	Unshielded primary air-kerma 1 m per kVp ( $K_p^1(kVp)$ )	a1(90, kVp)	a1(135, kVp)	Ks (90, kVp)	Ks(135, kVp)
40	0.00000	3.77384	5.71912	0.00000	0.00000
45	0.00026	3.85384	5.79912	0.00000	0.00000
50	0.00883	3.93384	5.87912	0.00001	0.00002
55	0.07956	4.01384	5.95912	0.00015	0.00022
60	0.06075	4.09384	6.03912	0.00011	0.00017
65	0.60481	4.17384	6.11912	0.00121	0.00178
70	1.12256	4.25384	6.19912	0.00229	0.00335
75	0.06376	4.33384	6.27912	0.00013	0.00019
80	0.02663	4.41384	6.35912	0.00005	0.00008
85	0.00000	4.49384	6.43912	0.00000	0.00000
90	0.01534	4.57384	6.51912	0.00003	0.00004
95	0.00000	4.65384	6.59912	0.00000	0.00000
100	0.00000	4.73384	6.67912	0.00000	0.00000
105	0.00244	4.81384	6.75912	0.00000	0.00000
110	0.00000	4.89384	6.83912	0.00000	0.00000
115	0.00000	4.97384	6.91912	0.00000	0.00000
120	0.00000	5.05384	6.99912	0.00000	0.00000
125	1.14383	5.13384	7.07912	0.00283	0.00389
130	0.00000	5.21384	7.15912	0.00000	0.00000

By summing the scatter air-kerma for each kVp interval we obtain the scatter air-kerma for the floor of the facility B.

**Table 4.16: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for the floor of the facility B.**

Side-scatter (90) (mGy patient <sup>-1</sup> )	Forward/backward-scatter (135) (mGy patient <sup>-1</sup> )
0.00690	0.00980

Table 4.17 shows the scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the chest-Bucky of the facility B.

**Table 4.17: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each kVp interval for the chest-Bucky of the facility B.**

kVp	Unshielded primary air Kerma 1 m per kVp ( $K_p^1(kVp)$ )	a1(90, kVp)	a1(135, kVp)	Ks (90, kVp)	Ks(135, kVp)
50	0.00000	3.93384	5.87912	0.00000	0.00000
55	0.00000	4.01384	5.95912	0.00000	0.00000
60	0.00000	4.09384	6.03912	0.00000	0.00000
65	0.01240	4.17384	6.11912	0.00003	0.00005
70	0.62066	4.25384	6.19912	0.00187	0.00273
75	0.00663	4.33384	6.27912	0.00002	0.00002
80	0.04349	4.41384	6.35912	0.00014	0.00019
85	0.04930	4.49384	6.43912	0.00016	0.00022
90	0.13847	4.57384	6.51912	0.00045	0.00064
95	0.15863	4.65384	6.59912	0.00052	0.00074
100	0.20757	4.73384	6.67912	0.00069	0.00098
105	0.00806	4.81384	6.75912	0.00002	0.00003
110	0.00602	4.89384	6.83912	0.00002	0.00002
115	0.00582	4.97384	6.91912	0.00002	0.00002
120	0.00000	5.05384	6.99912	0.00000	0.00000
125	0.64150	5.13384	7.07912	0.00234	0.00322
130	0.00000	5.21384	7.15912	0.00000	0.00000

By summing the scatter air-kerma for each kVp interval we obtain the scatter air-kerma for the chest-bucky of the facility B.

**Table 4.18: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for the chest-bucky of the facility B.**

Side-scatter (90) (mGy patient <sup>-1</sup> )	Forward/backward-scatter (135) (mGy patient <sup>-1</sup> )
0.00630	0.00890

Table 4.19 shows scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each radiography installation within facility A and facility B

**Table 4.19: Scatter air-kerma at 1 meter from the source of scatter for 90 and 135 degree scatter for each radiography installation within facility A and facility B.**

Scatter angle		K <sub>s</sub> (mGy patient <sup>-1</sup> ) Facility A	K <sub>s</sub> (mGy patient <sup>-1</sup> ) Facility B	K <sub>s</sub> (mGy patient <sup>-1</sup> ) NCRP-147
90 degree	Floor	$9.7 \times 10^{-3}$	$6.9 \times 10^{-3}$	$23.0 \times 10^{-3}$
	Chest Bucky	$6.8 \times 10^{-3}$	$6.3 \times 10^{-3}$	$4.9 \times 10^{-3}$
	All barriers	$33.0 \times 10^{-3}$	$31.0 \times 10^{-3}$	$34.0 \times 10^{-3}$
135 degree	Floor	$14.0 \times 10^{-3}$	$9.8 \times 10^{-3}$	$33.0 \times 10^{-3}$
	Chest Bucky	$9.8 \times 10^{-3}$	$8.9 \times 10^{-3}$	$6.9 \times 10^{-3}$
	All barriers	$47.0 \times 10^{-3}$	$44.0 \times 10^{-3}$	$48.0 \times 10^{-3}$

For the floor of facility A and facility B Table 4.15 shows that side-scatters and forward/backscatters are lower than the standard values and for the chest Bucky, side-scatter and forward/backscatter is bigger than the standard value. These result show

that for facility A and facility B, the major part of patient examinations are done at the chest Bucky.

#### 4.1.4 Leakage air-kerma at 1 meter of the source of tube

The Tables 4.20, 4.21, 4.22, and 4.23 give the unshielded leakage air-kerma at 1 meter of the tube for each radiography installation for facility A and facility B.

**Table 4.20: Leakage air-kerma at 1 meter of the tube for the floor of the facility A.**

kVp	Unshielded primary air-kerma 1 m per kVp ( $K_p^1(kVp)$ )	Leakage air-kerma $K_L(kVp)$
40	0.00000	0.00000
45	0.00766	0.00001
50	0.08562	0.00010
55	0.02665	0.00003
60	0.04995	0.00006
65	0.04941	0.00006
70	0.74801	0.00091
75	0.20859	0.00025
80	0.40976	0.00049
85	0.08569	0.00010
90	0.25905	0.00031
95	0.29952	0.00036
100	0.06007	0.00007
105	0.26960	0.00033
<b>Total leakage air-kerma (mGy patient<sup>-1</sup>)</b>		<b>0.00300</b>

**Table 4.21: Leakage air-kerma at 1 meter of the tube for the chest-Bucky of the facility A.**

<b>kVp</b>	<b>Unshielded primary air- erma 1 m per kVp (<math>K_P^1(kVp)</math>)</b>	<b>Leakage air-kerma <math>K_L(kVp)</math></b>
50	0.00000	0.00000
55	0.00723	0.00001
60	0.18683	0.00042
65	0.23033	0.00052
70	0.69846	0.00157
75	0.60139	0.00135
80	0.63058	0.00142
85	0.25935	0.00058
90	0.10595	0.00024
95	0.11844	0.00026
100	0.16219	0.00036
105	0.01008	0.00002
110	0.05915	0.00013
115	0.04857	0.00011
120	0.17802	0.00040
125	0.08893	0.00020
130	0.01385	0.00001
135	0.00000	0.00001
<b>Total leakage air-kerma (mGy patient<sup>-1</sup>)</b>		<b>0.00770</b>



**Table 4.22: Leakage air-kerma at 1 meter of the tube for the floor of the facility****B.**

<b>kVp</b>	<b>Unshielded primary air Kerma 1 m per kVp (<math>K_p^1(kVp)</math>)</b>	<b>Leakage air Kerma <math>K_L(kVp)</math></b>
40	0.00000	0.00000
45	0.00026	0.00000
50	0.00883	0.00001
55	0.07956	0.00005
60	0.06075	0.00004
65	0.60481	0.00041
70	1.12256	0.00076
75	0.06376	0.00004
80	0.02663	0.00001
85	0.00000	0.00000
90	0.01534	0.00001
95	0.00000	0.00000
100	0.00000	0.00000
105	0.00244	0.00000
110	0.00000	0.00000
115	0.00000	0.00000
120	0.00000	0.00000
125	1.14384	0.00078
130	0.00000	0.00000
<b>Total leakage air Kerma (mGy patient<sup>-1</sup>)</b>		<b>0.00210</b>

**Table 4.23: Leakage air-kerma at 1 meter of the tube for the chest-Bucky of the facility B.**

<b>kVp</b>	<b>Unshielded primary air-kerma 1 m per kVp (<math>K_p^1(kVp)</math>)</b>	<b>Leakage air-kerma <math>K_L(kVp)</math></b>
50	0.00000	0.00000
55	0.00000	0.00000
60	0.00000	0.00000
65	0.01240	0.00004
70	0.62065	0.00220
75	0.00663	0.00002
80	0.04348	0.00015
85	0.04930	0.00017
90	0.13847	0.00049
95	0.15863	0.00056
100	0.20757	0.00074
105	0.00805	0.00002
110	0.00602	0.00002
115	0.00582	0.00002
120	0.00000	0.00000
125	0.64150	0.00228
130	0.00000	0.00000
<b>Total leakage air-kerma (mGy patient<sup>-1</sup>)</b>		<b>0.00680</b>

Table 4.24 presents the leakage air-kerma at 1 meter of the focal spot of the tube for each radiography installation for facility A and for facility B compared with standard values from NCRP-147.

**Table 4.24: Leakage air-kerma at 1 meter of the focal spot of the tube for each radiography installation for facility A and for facility B compared with standard values from NCRP-147.**

Radiographic room	Leakage air-kerma at 1 meter (mGy patient <sup>-1</sup> ) Facility A	Leakage air-kerma at 1 meter (mGy patient <sup>-1</sup> ) Facility B	Leakage air-kerma at 1 meter (mGy patient <sup>-1</sup> ) NCRP-147
Floor	$3 \times 10^{-3}$	$2.1 \times 10^{-3}$	$1.4 \times 10^{-4}$
Chest-Bucky	$7.7 \times 10^{-3}$	$6.8 \times 10^{-3}$	$3.9 \times 10^{-4}$
All barriers	$1.1 \times 10^{-2}$	$8.9 \times 10^{-3}$	$5.3 \times 10^{-4}$

#### 4.1.5. Unshielded secondary air-kerma at $d_s = d_L = 1$ meter

The unshielded secondary air-kerma at  $d_s = d_L = 1$  meter has two components:

- The unshielded secondary air-kerma at  $d_s = d_L = 1$  meter composed of Leakage and side-Scatter radiation.
- The unshielded secondary air-kerma at  $d_s = d_L = 1$  meter composed of Leakage and Forward/Backward-Scatter radiation.

Table 4.25 provides the unshielded secondary air-kerma at  $d_s = d_L = 1$  meter each of the two components.

**Table 4.25: Leakage and side-scatter and leakage and forward/backward-scatter for facility A and for facility B**

Radiographic room	Facility A		Facility B	
	Leakage and side-scatter (mGy patient <sup>-1</sup> )	Leakage and forward/backward-scatter (mGy patient <sup>-1</sup> )	Leakage and side-scatter (mGy patient <sup>-1</sup> )	Leakage and forward/backward-scatter (mGy patient <sup>-1</sup> )
Floor	$1.27 \times 10^{-2}$	$1.70 \times 10^{-2}$	$9.00 \times 10^{-3}$	$1.19 \times 10^{-2}$
Chest-Bucky	$1.45 \times 10^{-2}$	$1.75 \times 10^{-2}$	$1.31 \times 10^{-2}$	$1.57 \times 10^{-2}$
All barriers	$4.35 \times 10^{-2}$	$5.77 \times 10^{-2}$	$3.99 \times 10^{-2}$	$5.29 \times 10^{-2}$

**4.1.6. Primary barriers thicknesses for facility A and for facility B**

A total of 729 patients have been examined for three months in the facility A, which gives an average of 60 patients in a week. However for busy week the number of patients may reach 90. For facility B, a total of 706 patients have been examined for three months, then an average of 60 patients is assumed and for busy week it may reach 90. For the two facilities the shielding material used for the construction of primary barriers is the ordinary concrete of density  $2.35 \text{ g/cm}^3$  and the existing primary barriers thickness is 30 cm.

**Table 4.26: Calculated chest-Bucky wall thickness for facility A and for facility B**

Rad room	Facility A		Facility B	
	number of patients per week		number of patients per week	
	Average	Busy	Average	Busy
	60	90	60	90
Calculated chest-bucky wall thickness (in mm)	<b>41</b>	<b>46</b>	<b>29</b>	<b>33</b>

For these two facilities, the radiography room is located at the first floor, then the calculation of the thickness of the floor is not useful. There is no workers, patient or public to be protected there.

#### 4.1.7. Secondary barriers thicknesses for facility A and for facility B

Table 4.27 provides the calculated thickness of each barrier for facility A and B. For both of these facility the shielding material used for the construction of secondary barriers is the ordinary concrete of density  $2.35 \text{ g/cm}^3$  except from the lead plate for the control windows which is in plate glass, and the existing secondary barriers thickness is 30 cm. The thicknesses are all measured in millimetre (mm).

**Table 4.27: Secondary barriers thicknesses for facility A and for facility B**

Rad room	Facility A		Facility B	
	number of patient per week		number of patient per week	
	Average	Busy	Average	Busy
	60	90	60	90
Calculated chest-Bucky wall (wall1) thickness (in mm)	24	28	23	27
Calculated ceiling thickness (in mm)	18	21	17	20
Calculated room opposite to chest Bucky (wall2) (in mm)	14	16	9	12
Calculated cross-table lateral wall (wall4) (in mm)	2	4	9	12
Calculated secondary wall Calculated opposite to the cross-table lateral wall (wall3) (in mm)	9	7	10	13
Control wall (plate glass in mm)	10	12	8	11

#### 4.1.8. Average DLP for head and for body scan in facility A and in facility B

Table 4.28 shows the average DLP for head and for body scan in facility A and in facility B.

**Table 4.28: Average DLP for head and for body scan in facility A and in facility B.**

Facility A		Facility B		NCRP-147	
Average DLP (mGy cm) (head)	Average DLP (mGy cm) (body)	Average DLP (mGy cm) (head)	Average DLP (mGy cm) (body)	Average DLP (mGy cm) (head)	Average DLP (mGy cm) (body)
1830 ± 610	859 ± 438	806 ± 346	305 ± 154	1200	550

#### 4.1.9. Weekly secondary air-kerma at 1 meter of the isocentre of the gantry for facility A and facility B

For the facility A, the weekly number of patients undergoing body scans is 25 for the average, and 30 for busy weeks, and that of patients undergoing head scans is 15 for the average, and 20 for busy weeks. For facility B, the number of patients for body scans is 17 for the average, and 20 for busy weeks and that of head scans is 14 for the average and 20 for busy weeks.

Table 4.29 shows weekly secondary air Kerma at 1 meter of the isocentre of the gantry for facilities A and B.

**Table 4.29: Weekly secondary air-kerma at 1 meter of the isocentre of the gantry for facilities A and B.**

Facility A						Facility B					
Head $K_{sec}^1(head)$		Body $K_{sec}^1(body)$		Total $K_{sec}^1$		Head $K_{sec}^1(head)$		Body $K_{sec}^1(body)$		Total $K_{sec}^1$	
Average	busy	Average	busy	average	busy	Average	busy	average	busy	average	Busy
2.50	3.30	7.70	9.30	10.20	12.60	1.01	1.45	0.62	0.73	1.63	2.18

#### 4.1.10. Secondary barriers thicknesses for facility A and for facility B

Table 4.30 shows the secondary barriers thicknesses for facility A and for facility B.

**Table 4.30: Secondary barriers thicknesses for facility A and for facility B.**

Secondary barrier Thicknesses (in mm)	Facility A		Facility B	
	number of patient per week		number of patient per week	
	Average	Busy	Average	Busy
Wall 1 (in mm)	14	16	6	9
Wall 2 (in mm)	27	29	3	5
Wall 3 (in mm)	26	28	8	11
Wall 4 (in mm)	21	23	7	10

#### 4.1.11. Dose rate measurements

##### 4.1.11.1 Dose rate measurement for the radiography room of facility A.

Table 4.31 shows the dose rate at some given location for the radiography room of facility A.

**Table 4.31: Dose rate at some given location for the radiography room of facility****A**

<b>LOCATION</b>	<b>Distance from the tube (m)</b>	<b>DOSE RATE (<math>\mu\text{Sv}/\text{h}^{-1}</math>)</b>	<b>REMARKS</b>
<b>Wall 1</b>	2.1	0.06	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Wall 2</b>	2.65	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Wall 3</b>	1.55	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Wall 4</b>	4.15	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Door</b>	1.55	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Screen</b>	2.4	1.41	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv}/\text{h}^{-1}$ )
<b>Ceiling</b>	2.3	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv}/\text{h}^{-1}$ )

**4.1.11.2 Dose rate measurement for the CT room of facility A**

Table 4.32 shows the dose rate at some given location for the CT room of facility A.

**Table 4.32: Dose rate at some given location for the CT room of facility A.**

LOCATION	Distance from the isocentre (m)	DOSE RATE ( $\mu\text{Sv h}^{-1}$ )	REMARKS
Wall 1	4.25	0.07	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Wall 2	2.30	1.02	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Wall 3	2.75	0.22	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Wall 4	3.40	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Door	3.60	0.65	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Screen (control room)	4.25	0.24	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Door of the control room	4.25	0.09	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Ceiling	3.10	0.06	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )

**4.1.11.3 Dose rate measurement for the radiography room of facility B**

Table 4.33 shows the dose rate at some given location for the radiography room of facility B.



**Table 4.33: Dose rate at some given location for the radiography room of facility B.**

LOCATION	Distance from the tube (m)	DOSE RATE ( $\mu\text{Sv h}^{-1}$ )	REMARKS
Wall 1	2.10	0.07	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Wall 2	3.50	2	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Wall 3	3.30	0.18	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Wall 4	1.18	1.96	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Door		-----	The entrance is not protected
Screen of the control room	2.00	1.5	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Ceiling	2.70	0.09	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )

#### 4.1.11.4 Dose rate measurement for the CT room of facility B

Table 4.34 shows the dose rate at some given location for the CT room of facility B.



**Table 4.34: Dose rate at some given location for the CT room of facility B.**

LOCATION	Distance from the isocentre (m)	DOSE RATE ( $\mu\text{Sv h}^{-1}$ )	REMARKS
Wall 1	3.50	0.18	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Wall 2	5.60	0.49	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Wall 3	2.50	0.15	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Wall 4	2.80	0.25	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Door	3.80	0.09	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )
Screen of the control room	3.10	2.65	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Door of the control room	3.50	0.12	Lower than the derived dose rate limit ( $7.5 \mu\text{Sv/h}^{-1}$ )
Floor	2.90	0.08	Lower than the derived dose rate limit ( $2.5 \mu\text{Sv/h}^{-1}$ )

**Remarks:**

- The derived dose rate limit is  $7.5 \mu\text{Sv/h}^{-1}$  for controlled area and  $2.5 \mu\text{Sv/h}^{-1}$  for non-control (uncontrolled area) [13].
- The measurements was done three time and average to get the final values
- The background radiation for the facility A is  $0.06 \mu\text{Sv/h}^{-1}$ ;
- The background radiation for the facility B is  $0.07 \mu\text{Sv/h}^{-1}$
- The measurements have been done at 0.3 m behind each barrier except from the ceiling which have been measured at 0.5 m.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATION

#### 5.1 Conclusion

This study was designed to assess the structural shielding within two medical diagnostic imaging facilities and check whether these structural shielding in place provides adequate protection of workers and the public so that doses received are below the design dose limit established by the regulatory authority.

The assessment for general radiography was based on 729 examinations for facility A and 706 examinations for facility B. For computed tomography (CT) rooms, a total of 293 body and 190 head procedures were used for facility A, and 195 body and 160 head procedures for facility B. For the general radiography, the workload distribution and the normalized workload per patient have been determined for each room type (floor and chest-Bucky).

For facility A, the normalized workload per patient was 0.96 mA min patient<sup>-1</sup> for the floor and 1.25 mA min patient<sup>-1</sup> for the chest-bucky, the unshielded primary air-kerma per patient for the floor was 2.56 mGy patient<sup>-1</sup> and 3.4 mGy patient<sup>-1</sup> for the chest-bucky in the general radiography room. The average DLP were 1830 ± 610 mGy cm and 859 ± 438 mGy cm for head and body respectively in the CT room.

For facility B, the normalized workload per patient was 1.14 mA min patient<sup>-1</sup> for the floor and 0.53 mA min patient<sup>-1</sup> for the chest-bucky, the unshielded primary air-kerma per patient was 3.13 for the floor and 1.9 for the chest-bucky in general radiography room. The average DLP were 806 ± 346 mGy cm and 305 ± 154 mGy cm for head

and body respectively in the CT room. For each of the two facilities, the thicknesses of the walls that are recommended are smaller than the thicknesses of the walls in place.

Dose rate measurements confirmed that the different barriers thicknesses are enough to maintain the dose receive by workers and the public below the required dose limits.

## 5.2 Recommendations

The followings are recommendations from the study are as follows:

### Diagnostic X-ray Facilities

- Re-evaluation of shielding adequacy should be done by the RPO or qualified experts when the factors that affect the shielding integrity changes;
- A door with appropriate shielding thickness should be provided in facility B to protect people at the entrance of the radiography room;
- Each medical imaging facility should have a radiation protection officer (RPO) to oversee the implementation of the facility Radiation Protection Programme;
- The staff should be periodically trained;
- A warning light should be placed at the entrance to any room;
- A sign should also be posted to indicate that the X-ray room is a controlled area;
- QC tests should be done periodically to ensure the x-ray equipment is functioning properly with time.

### **Regulatory Authority**

The regulatory authority should provide applicable regulations and guidance documents under medical exposure control which should include requirements for safety assessment of Structural Shielding Design evaluation for Medical X-ray Imaging facilities.



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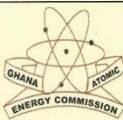
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## APPENDIX

A1: calibration certificate of the EBERLINE RO20

RPI/SSDL.Cal. Cert. No: RSM/22/2016	Page 1 of 2
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**GHANA ATOMIC ENERGY COMMISSION  
RADIATION PROTECTION INSTITUTE  
SECONDARY STANDARD DOSIMETRY LABORATORY**

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CALIBRATION CERTIFICATE No. **RSM/22/2016**  
Number of Pages: **2**  
Date of Issue: **16/03/2016**

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The following Survey Meter from: **NATIONAL AUTHORITY OF RADIATION PROTECTION AND NUCLEAR SAFETY OF BURKINA FASO**

---

has been calibrated at the *Secondary Standard Dosimetry Laboratory of the Radiation Protection Institute, Ghana Atomic Energy Commission:*

Instrument:	Manufacturer	Model	Serial No.
<b>DOSE RATE METER</b>	<b>THERMO ELECTRON CORPORATION</b>	<b>EBERLINE RO20 SI</b>	<b>1092</b>

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Calibration Period: from: **15/03/2016** to: **16/03/2016**  
Recalibration: 1 year Recommended

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**CALIBRATION DATA:**  
*Radiation Quality:*  $^{137}\text{Cs}$

*Instrument parameters during calibration:*

RESPONSE:	M
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*Environmental conditions during calibration*

Temperature	Pressure	Relative Humidity
23.40 °C	101.95kPa	52%

The SSDL in Ghana is a member of the IAEA/WHO Secondary Standards Dosimetry Laboratory. This certificate may not be reproduced other than in full, except with the prior written approval of the SSDL/RPI

RPI/SSDL.Cal.Cert. No: RSM/22/2016

Page 2 of 2

**Calibration Conditions**

<b>Instrument positioning:</b>	<b>Monitor perpendicular to beam axis</b>
<b>Calibration reference Point:</b>	<b>Geometrical centre of monitor</b>
<b>Source to Detector Distance:</b>	<b>1 – 7 m according to H*(10) rate</b>
<b>Field Size:</b>	
<b>Beam Direction</b>	<b>Horizontal</b>

**CALIBRATION RESULTS**

Calibrations have been performed with the substitution method using reference chamber LS-01 (S/N 227) and the electrometer PTW UNIDOS (S/N 20243). The reference chamber has been calibrated at the IAEA calibration Laboratory in Seibersdorf, Austria and PTB-Germany.

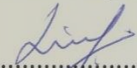
**Calibration factors per scale**

<b>Instrument S/N</b>	<b>Range</b>	<b>Calibration factor<sup>(1)</sup></b>	<b>Uncertainty<sup>(2)</sup></b>
<b>1092</b>	<b>500 <math>\mu</math>Sv/h</b>	<b>0.17</b>	<b>10%</b>
	<b>5 mSv/h</b>	<b>0.19</b>	<b>10%</b>


(1) Mean Calibration Factor: Ratio of the true value of H\*(10) to the instrument indication

(2) Coverage Factor:  $k = 2$ .

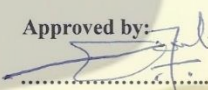
**Calibration performed by:**

  
.....  
Daniel Nii Adjei

**Supervised by:**

  
.....  
Dr. John Owusu-Banahene  
Manager, HPIC

**Approved by:**

  
.....  
Prof. E. O. Darko  
Director, RPI

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A3: Extract of CT data for head examinations in facility A

Patients	DLP	mAs	kVp	Patients	DLP	mAs	kVp	Patients	DLP	mAs	kVp	Patients	DLP	mAs	kVp	Patients	DLP	mAs	kVp
1	1029	115	120	26	1004	220	130	51	2098	460	130	76	2475	690	130	101	2376	460	130
2	1979	440	130	27	2368	669	120	52	1084	230	130	77	101	35	130	102	1029	230	130
3	2190	440	130	28	2479	440	130	53	2936	690	130	78	1816	440	130	103	1022	230	130
4	992	220	130	29	2687	500	130	54	2020	460	130	79	1926	460	130	104	4520	750	130
5	2093	460	130	30	269	123	130	55	1564	230	130	80	1676	230	130	105	2109	460	130
6	2095	460	130	31	2461	460	130	56	1084	230	130	81	2298	460	130	106	2109	480	130
7	2952	500	130	32	2181	460	130	57	2078	460	130	82	2555	857	120	107	2700	460	130
8	2510	599	130	33	2073	460	130	58	1709	436	110	83	1915	460	130	108	1735	250	130
9	2315	440	130	34	492	181	130	59	2388	460	130	84	2020	460	130	109	2115	500	130
10	2517	500	130	35	2109	460	130	60	587	170	130	85	2059	460	130	110	1898	470	130
11	351	206	130	36	1731	230	130	61	2156	460	130	86	852	214	110	111	2199	500	130
12	1849	440	130	37	2824	916	120	62	1038	582	130	87	2058	460	130	112	2280	460	130
13	889	230	130	38	988	230	130	63	2168	460	130	88	2076	460	130	113	311	146	130
14	1398	382	110	39	2247	460	130	64	889	220	130	89	304	230	130	114	2872	768	110
15	2287	460	130	40	1820	230	130	65	2059	482	130	90	1452	563	110	115	1998	460	130
16	2335	260	130	41	1745	230	130	66	3466	710	130	91	2345	460	130	116	3000	460	130
17	2453	740	120	42	2270	460	130	67	682	123	130	92	1937	460	130	117	1127	230	130
18	940	230	130	43	2361	645	110	68	2002	440	130	93	1391	230	130	118	460	300	130
19	238	106	130	44	2235	460	130	69	2100	460	130	94	2043	460	130	119	829	306	130
20	2577	500	130	45	454	163	130	70	371	294	130	95	2469	660	130	120	987	220	130
21	2440	716	120	46	819	347	130	71	821	345	130	96	475	173	130	121	1476	398	110
22	2439	460	130	47	348	140	130	72	2051	460	130	97	2387	460	130	122	2353	460	130
23	2004	460	130	48	1218	250	130	73	1882	440	130	98	595	176	110	123	2391	620	110
24	2192	460	130	49	996	230	130	74	2258	440	130	99	2491	440	130	124	695	278	130
25	1053	220	130	50	2220	460	130	75	1648	442	110	100	2446	472	130	125	1071	230	130

A4: Extract of CT data for body examinations in facility B

Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP	Patient	DLP	Patients	DLP
1	307	26	439	51	440	76	225	101	288	126	313	151	565	176	143
2	529	27	190	52	136	77	212	102	262	127	293	152	406	177	265
3	84	28	275	53	232	78	520	103	264	128	229	153	243	178	181
4	160	29	503	54	229	79	287	104	148	129	259	154	560	179	256
5	676	30	291	55	136	80	387	105	295	130	160	155	555	180	370
6	206	31	281	56	753	81	623	106	155	131	675	156	777	181	323
7	276	32	415	57	326	82	97	107	450	132	424	157	855	182	254
8	313	33	477	58	144	83	437	108	560	133	375	158	152	183	238
9	138	34	148	59	148	84	200	109	525	134	545	159	316	184	370
10	274	35	128	60	127	85	167	110	340	135	375	160	472	185	239
11	90	36	139	61	149	86	121	111	434	136	271	161	705	186	565
12	131	37	554	62	177	87	105	112	154	137	84	162	95	187	518
13	146	38	220	63	403	88	155	113	134	138	408	163	375	188	122
14	361	39	120	64	365	89	432	114	241	139	80	164	156	189	503
15	153	40	735	65	155	90	130	115	704	140	124	165	164	190	124
16	414	41	225	66	164	91	265	116	135	141	160	166	700	191	547
17	390	42	501	67	143	92	302	117	113	142	131	167	150	192	188
18	126	43	115	68	526	93	160	118	253	143	388	168	219	193	370
19	202	44	225	69	196	94	152	119	152	144	292	169	165	194	524
20	501	45	735	70	540	95	390	120	175	145	761	170	168	195	621
21	753	46	340	71	610	96	238	121	149	146	85	171	110		
22	135	47	240	72	110	97	318	122	584	147	227	172	527		
23	228	48	59	73	792	98	148	123	168	148	327	173	220		
24	231	49	541	74	142	99	160	124	130	149	204	174	136		
25	135	50	191	75	716	100	165	125	432	150	170	175	133		

A5: Extract CT data for head examinations in facility B

Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP	Patients	DLP
1	878	26	705	51	53	76	1014	101	1347	126	1452
2	1354	27	832	52	303	77	673	102	735	127	631
3	906	28	1263	53	347	78	457	103	1807	128	1000
4	561	29	1540	54	324	79	541	104	713	129	1899
5	872	30	249	55	815	80	457	105	1306	130	745
6	836	31	396	56	856	81	1504	106	1419	131	708
7	505	32	362	57	628	82	366	107	728	132	1158
8	380	33	97	58	588	83	386	108	500	133	1264
9	597	34	200	59	1400	84	812	109	544	134	327
10	376	35	600	60	945	85	582	110	1533	135	1288
11	524	36	412	61	812	86	1423	111	735	136	1438
12	318	37	416	62	675	87	1412	112	876	137	520
13	498	38	251	63	1154	88	460	113	912	138	1326
14	317	39	518	64	540	89	1700	114	645	139	924
15	288	40	475	65	328	90	985	115	323	140	1400
16	289	41	457	66	570	91	1250	116	1530	141	821
17	370	42	485	67	899	92	753	117	918	142	923
18	369	43	384	68	724	93	1389	118	875	143	745
19	725	44	486	69	360	94	516	119	1678	144	1474
20	835	45	367	70	1450	95	448	120	528	145	877
21	665	46	540	71	406	96	616	121	1256	146	1354
22	470	47	427	72	982	97	1515	122	679	147	906
23	940	48	47	73	348	98	1448	123	893	148	871
24	465	49	349	74	1144	99	1389	124	903	149	535
25	105	50	796	75	1796	100	1085	125	826	150	1504

A6: Extract of data for Rad Rom (chest-bucky) examination in facility A

Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs
1	1	118	80	16	1	75	40	31	2	65	42	45	1	122	4	62	2	110	16
2	3	60	20		1	80	80	32	3	60	20	46	1	75	80		1	95	10
3	1	70	40	17	9	70	40	33	1	65	25		2	85	85	63	1	95	10
	1	70	32	18	2	122	4		1	65	20	47	2	70	50		1	108	12
	2	65	50	19	2	65	50		3	65	25	48	1	75	80	64	2	60	40
	4	60	20		3	80	80	34	2	55	20		1	85	85	65	1	95	10
4	2	65	25	20	1	55	20	35	1	65	20	49	1	122	4	66	2	95	10
5	2	65	40	21	2	60	20		2	60	20		1	65	32	67	2	105	12
	3	122	4		2	65	40	36	1	75	80	50	1	122	4	68	5	60	40
6	2	122	4		1	80	80		1	80	80	51	2	122	4	69	2	90	8
7	1	75	80	22	1	60	25	37	8	65	80		1	65	32	70	1	90	8
	2	80	80	23	2	122	5	38	1	122	4	52	3	60	40		1	105	12
8	1	122	4		1	126	7		1	126	6	53	1	107	10	71	2	70	80
9	1	70	40	24	2	122	5	39	1	75	80	54	3	60	40	72	1	70	62.5
10	2	60	20	25	1	65	32		2	80	80	55	3	70	50		1	75	80
	2	55	20		1	65	25	40	1	75	80	56	4	60	40	73	1	115	12
11	1	60	20	26	4	70	40		2	80	80		1	65	40	74	1	95	10
	1	56	20	27	1	75	80	41	2	55	20	57	1	95	10	75	1	108	10
12	1	120	4		2	85	85	42	1	65	63		1	110	16	76	1	80	5
13	2	45	5	28	1	75	80		1	75	80	58	3	80	100	77	1	120	20
14	2	65	25		2	85	85		1	75	80	59	2	70	80	78	1	110	12
	2	65	32	29	1	122	4		2	80	80	60	2	60	40	79	2	60	50
	2	70	40		2	125	8	43	1	65	25		2	85	6		2	55	32
15	9	65	80	30	2	75	80	44	1	75	80	61	1	95	10	80	2	116	8

A7: Extract of data for Rad Rom (floor) examination in facility A

Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs	Patients	Number of procedures	kVp	mAs
1	4	50	10	19	1	65	62.5	39	2	48	8	62	2	48	10	83	1	50	10
2	2	50	12		16	80	125	40	2	48	8	63	5	47	8	84	2	65	40
3	3	48	8	20	2	47	6	41	16	70	62.5	64	2	47	7	85	5	52	10
4	2	48	8	21	3	50	10	42	12	70	62.5	65	2	45	5	86	8	70	62.5
	2	60	32	22	2	47	6.4	43	4	52	10	66	3	47	6	87	15	70	80
5	1	50	10		1	46	6.4	44	10	50	10	67	6	50	10	88	7	50	10
	1	47	6	23	2	49	10	45	2	54	10	68	2	45	5	89	7	49	10
6	11	70	80	24	3	60	32	46	2	45	5	69	4	46	6	90	1	65	50
7	5	70	80	25	4	46	6	47	2	48	8	70	4	50	10	91	2	50	10
8	2	63	40	26	2	48	8	48	2	55	16	71	3	47	7		1	50	10
	2	60	40	27	11	70	80	49	2	54	12.5	72	2	50	10		1	47	8
9	2	46	6	28	2	48	8	50	1	70	62.5	73	2	48	8	92	2	45	5
10	13	75	100		5	60	40		10	70	80		2	50	8	93	2	45	5
11	1	48	8	29	2	47	6	51	2	47	8	74	2	46	6	94	3	45	5
	1	50	8	30	2	46	8	52	8	70	62.5	75	11	80	100	95	3	47	6
12	1	47	6	31	2	56	12.8	53	2	70	80	76	15	90	120	96	2	47	5
	2	48	8	32	2	62	50	54	2	46	6	77	3	70	80	97	2	47	6
	1	47	8	33	3	65	62.5	55	3	75	80	78	1	68	50	98	3	45	5
13	2	68	16	34	8	50	10	56	4	52	10	79	8	70	62.5	99	5	49	8
14	2	70	20	35	4	48	8	57	20	95	120	80	3	52	10	100	3	46	6
	3	50	16	36	3	60	64	58	6	52	12		1	60	20	101	3	47	7
15	2	50	12.8		2	49	12.5	59	4	50	10	81	2	50	10	102	2	60	50
16	4	45	5	37	2	58	40	60	6	60	40	82	2	47	6	103	2	49	8
17	4	45	4	38	2	45	5	61	19	102	120		4	52	10	104	2	50	12
18	2	48	8																

A8: Extract of data for Rad Rom (chest-bucky) examination in facility B

Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp
1	2	16	95	23	1	22	98	45	1	10	90	68	2	12	95	88	12	70	125
2	1	125	68	24	1	25	95	46	2	12	95	69	1	12	90	89	1	10	95
	1	320	68	25	1	15	98	47	1	15	95		1	20	95	90	1	10	95
3	2	20	90	26	1	10	95	48	1	70	125	70	1	15	90	91	1	20	95
4	2	10	85	27	1	12	90	49	2	12	80		1	32	98	92	1	10	80
5	1	20	90		1	20	95	50	1	22	98	71	1	10	90	93	2	60	68
6	1	20	90	28	1	10	80	51	1	320	68	72	1	10	90	94	1	320	68
7	1	20	90	29	1	125	68	52	1	80	90	73	1	320	68	95	1	16	95
8	1	10	78	30	1	10	90	53	2	125	65	74	1	12	92	96	1	125	68
9	2	20	85	31	1	320	68	54	1	32	65	75	1	12	95	97	1	125	68
10	4	14	85	32	2	10	90	55	1	12	90	76	4	40	68		1	320	68
11	2	20	90	33	1	15	98		1	32	95	77	2	125	68	98	1	20	90
12	1	15	95	34	1	125	68	56	1	125	68		1	320	68	99	3	10	80
13	1	12	95		1	320	68		1	320	68	78	3	60	68	100	1	10	85
14	2	34	98	35	1	12	68	57	1	10	95	79	1	10	90	101	1	10	90
15	1	15	90		2	125	68	58	1	22	98	80	1	32	98	102	2	20	90
	8	60	68	36	8	70	68	60	2	12	90	81	1	10	85	103	1	10	85
16	1	12	95	37	2	15	95	61	2	20	95	82	2	10	78	104	1	10	85
17	1	20	98	38	1	15	90	62	1	15	95		1	20	85	105	3	10	85
18	1	25	98	39	3	125	98		1	32	98	83	2	15	98	106	1	12	95
19	2	15	85	40	1	15	95	63	1	12	90	84	1	10	80	107	1	58	78
20	8	70	125	41	3	28	98	64	4	70	125	85	1	17	90		1	15	98
21	2	20	95	42	1	15	80	65	1	32	98		3	32	98	108	1	18	95
22	1	20	95	43	4	20	80	66	1	25	98	86	1	22	98	109	1	20	90
				44	1	24	90	67	5	40	68	87	1	20	95	110	1	10	78

A9: Extract of data for Rad Rom (floor) examination in facility B

Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp	Patients	Number of procedures	mAs	kVp
1	1	32	68	24	2	320	125	44	1	38	58	65	1	32	65	85	1	6	58
2	3	10	65	25	1	32	68	45	8	50	55	66	1	64	68	86	8	68	64
3	1	10	65	26	2	10	58	46	1	10	55		1	54	68	87	1	125	67
4	1	125	65	27	1	20	75	47	2	25	62		2	32	55	88	2	8	58
5	1	64	68	28	5	32	58	48	2	32	65	67	1	50	68		1	6	58
6	1	125	65	29	4	64	68		1	8	48	68	2	32	55	89	1	20	90
7	5	68	64	30	8	68	125	49	1	12	55		1	54	68		8	68	64
8	4	68	64	31	4	50	65	50	1	12	65	69	1	10	65	90	1	25	75
9	1	6	58		2	20	90		2	8	58	70	1	32	68	91	8	54	68
	1	6	53	32	3	10	55	51	1	8	58	71	12	58	70	92	3	10	65
10	1	5	58	33	1	10	58	52	2	10	58	72	1	6	48	93	3	64	55
11	1	6	58	34	3	25	75	53	1	6	48	73	3	8	52	94	1	32	55
12	1	125	67	35	1	20	58	54	3	50	64	74	1	320	125	95	1	32	58
13	1	8	58		2	25	68	55	1	25	75	75	1	20	75	96	8	64	68
14	10	64	68	36	10	68	125	56	2	32	65	76	2	32	55	97	2	54	68
15	1	54	68	37	1	50	64		1	20	58	77	8	50	68	98	4	65	54
16	1	32	55	38	4	25	75	57	1	50	65	78	1	16	68	99	1	10	65
17	3	54	68	39	2	12	90	58	3	25	68	79	2	32	68	100	2	64	68
18	8	64	55	40	3	64	68	59	1	12	90	80	5	54	69	101	8	125	65
19	1	75	125		2	38	50	60	8	64	68	81	1	32	58	102	2	64	68
20	1	50	68	41	3	64	68	61	1	38	58	82	2	32	58		1	6	58
21	1	10	65	42	1	32	64	62	2	6.5	54	83	3	20	75	103	1	8	58
22	1	16	68	43	2	6	58	63	1	32	68	84	1	10	65	104	8	50	55
23	1	6.5	54		2	8	60	64	1	16	68		1	16	53	105	1	10	65