EVALUATION OF THE STRUCTURAL SHIELDING ADEQUACY OF SELECTED GENERAL X-RAY IMAGING FACILITIES IN SIERRA LEONE

By

Derrick Ivan Dunn

10586817

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DECLARATION

This is to certify that this thesis is the result of research work undertaken by Derrick Ivan Dunn towards the Degree of M.Phil. Nuclear Science and Technology in the Department of Medical Physics , School of Nuclear and Allied Science (SNAS), University of Ghana, Legon, under the supervision of Prof. Cyril Schandorf and Mr. Prince Gyekye

……………………… Date ……………………..

Derrick Ivan Dunn

(Student)

……………………… Date ……………………..

Prof. Cyril Schandorf

(Supervisor)

…………………….. Date …………………….

Mr. Prince Gyekye

(Co- Supervisor)

ABSTRACT

The purpose of this study was to assess the structural shielding of 5 selected general x-ray imaging facilities in Freetown, Sierra Leone and to propose a design which will serve as an alternative to lead lined doors thereby achieving the highest level of protection and safety. This research work is divided into two phases. The first part involves general assessment of the 5 selected general radiography facilities. From the data collected for facility FTN-CBD-01 with an estimated 132 patients week^{-1}, the normalized workload per patient was found to be 0.7mAmin Patient $^{-1}$ Rad Room (chest bucky) and 1.5mAmin Patient $^{-1}$ Rad Room (floor and other barriers). Facility FTN-04 has an estimated 90 patients week^{-1} and was found to have normalized workload per patient 0.5 mAmin Patient $^{-1}$ Rad Room (chest bucky) and 1.1 mAmin Patient $^{-1}$ Rad Room (floor and other barriers). These calculated values were compared with the recommended NCRP. 147 values and both facility and NCRP.147 values used to calculate required barrier thickness for both primary and secondary radiation with no significant difference recorded. Workload data for facilities FTN-CBD-02, FTN-CBD-03 and FTN-05 were not available during data collection and as such, derived NCRP 147 values were used to determine barrier shielding requirement. Calculations show the existing wall thickness of the facilities provides the required attenuation to reduce exposure to as low as reasonably achievable with the exception of 2 facilities which additional shielding will be required for the control room and entrance door. The second phase involves the use of the SimpleGeo tool kit to develop a three dimensional image of the architectural plans of all the facilities considered for the study using the detailed data of the facilities collected in the first phase of the study. Semiconductor detectors were modeled before and after each area or barrier of concerned for assessment. The x-ray tube of each facility was modeled using published procedures. A Monte Carlo N Particle 6 (MCNP6) input file was generated from the computational models of SimpleGeo for simulation. The x-ray spectrum that was used for simulation was generated at 100kV using SpeckCal software. The computational simulation is to aid verification of the values obtained from the calculations in the first part. Additionally, this will also aid propose alternative design or shielding material for facilities, thereby providing a radiation protection shielding alternative other than lead. The simulation measured the doses before and after each barrier and comparison was made with the ICRP dose requirement per day (mGy) for 20 exposures per day. Simulation results show that doses received behind the primary barriers was below ICRP recommended value of 0.00274 mGy per day with the exception of the doses at the entrance door and control room of 2 facilities. Alternative shielding materials and required thickness were recommended for facilities where appropriate lead thickness is not available.

DEDICATION

This thesis work is dedicated to Chermine, Leon, Darren and Darvin

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LIST OF ABBREVIATIONS AND SYMBOLS

θ	Scattering angle (measured from original primary beam direction)
a_1	Scatter fraction per primary beam at 1m primary distance
ACTI	Advanced Computational Technology Initiative
ACTL	Activation Library
B	Broad Beam Transmission
BIR	British Institute of Radiology
$B_{housing}$	Transmission of leakage radiation through x-ray tube housing
B_{film}	Transmission through film and cassette
B_P	Broad beam transmission of primary beam.
d_p	distance from source of radiation to occupied area
d_w	distance from film to barrier
d_f	Entrance surface to film distance
d_L	Leakage radiation distance from the x-ray tube to the occupied area
d_S	Scatter radiation distance from the center patient to the occupied area
d_{sec}	Secondary radiation distance derived from d_L and d_S
DAP	Dose Area Product
D_c	Annual Dose Constraint
CAD	Computer Aided Design
CSG	Constructive Solid Geometry
C	Positive constant in monte carlo simulation
ESD	Entrance Surface Dose
ENDF	Evaluated Nuclear Data File

ENDL	Evaluated Nuclear Data Library
EPDL	Evaluated Photon Data Library
FFD	Focus-film distance (m)
GAEC	Ghana Atomic Energy Commission
GM	Geiger Muller
HVL	Half Value Layer
IAEA	International Atomic Energy Agency
K_{film}	Film kerma (mGy)
K_{inc}	Incident air kerma
kVp	X-ray tube operating potential in kilovolt peak
$K_p(0)$	Weekly unshielded primary air kerma at a distance due to N number of patients
K_p^1	unshielded primary air kerma per patient at 1m calculated for a workload distribution of total workload per patient W_{norm}
K_{sec} (0)	Unshielded secondary air kerma at a distance due to N number of patient.
K_{sec}^1	Unshielded secondary air kerma per patient at 1m calculated for a workload distribution of total workload per patient.
K_w^1	Air kerma at 1m per unit workload due to primary beam.
MCNP	Monte Carlo Neutral Particle.
mAs	Current-time product in milliampere per Second
NSRPA	Nuclear Safety and Radiation Protection Authority
N	Number of Patients undergoing examinations in a given room.
N	Number of histories (Monte Carlo simulation)
P	Shielding design goal

R	Estimated Relative error (Monte Carlo simulation)
SSDL	Secondary Standards Laboratory
S_{max}	Maximum Scatter air kerma at 1m
Sdef	Source Definition
NCRP	National Council on Radiation Protection and Measurements
TLD	Thermoluninscient Dosimeters
TVL	Tenth Value Layer
T	Occupancy Factor
U	Use Factor
W	Workload
W_{norm}	Normalized Workload per patient
W_{tot}	Total Workload per week
x_{pre}	Pre shielding barrier thickness that intercepts the primary beam
$x_{barrier}$	barrier thickness that decreases air kerma to the occupied area to the appropriate shielding design goal.
$x_{\frac{1}{2}}$	Half-value (HVL) for an x-ray beam

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Diagnostic Radiology involves the use of x-rays to investigate the structure and function of human body to obtain the best possible diagnostic information with least radiation exposure to both patient and staff. It involves several techniques ranging from plain x-rays (radiography), x-ray of the breast (mammography), continuous imaging (fluoroscopy) and cross sectional imaging (CT scan). [1]

The National Council on Radiation Protection and Measurements (NCRP) has provided recommendations on the Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV in its Report No 49, 1976 [4.]

The NCRP report 147 focuses on recommendations on " Structural Shielding Design for Medical X-Ray Imaging Facilities" issued in 2004 and revised in 2005 [4].

Extensive use of the techniques and the associated equipment gives rise to radiation dose. In some cases however, these doses are not controlled and result in over exposure to patients and staff. [11]

Adequate radiation protection of patient, staff and the public is achieved by a combination of limitation of time spent in radiation field, maximization of the distance from the source of radiation exposure and design and structural shielding of the diagnostic Imaging facility.

The design and structural shielding of the diagnostic Imaging facility is most expensive of the system of radiation protection. Several international organizations have provided recommendations for the evaluation of the design and structural shielding of diagnostic x-ray facilities . [38]

During the conceptual stage for the introduction of a medical diagnostic x-ray facility it is regulatory requirement for the licensee/registrant to provide information on the design and structural shielding of the diagnostic Imaging facility to assure that there will be adequate protection of staff , patient and the public during the operation of the facility. Re-evaluation of the designed structural shielding is required when there is change in equipment and workload.

This work aims at a retrospective evaluation of some selected Medical Diagnostic X-ray Faculties in Sierra Leone since these has never been done since the introduction of these facilities for clinical use.

1.2 Problem Statement

The Nuclear Safety and Radiation Protection Authority (NSRPA) of Sierra Leone is the body mandated to ensure the protection of the public and workers against the harmful effects resulting from exposure to ionising radiation in the country. This responsibility is made possible through regulatory control activities.

The use of radioactive sources and irradiating devices in medical applications may give rise to radiation dose above recommended dose limits. Licensees are required to make an assessment of radiation shielding required to reduce radiation exposure to acceptable levels.

In Sierra Leone, there are currently 18 diagnostic x-ray facilities to serve the country's 6 million people for which 9 is authorised by the Regulatory Authority. However, all of these facilities have not fully met regulatory requirements with regards to shielding and design.

Prior to the construction of some of these facilities, there was no established regulatory body and as such radiation shielding design was not taken into consideration. Following the establishment of the Regulatory Authority, several inspections and follow up inspections have been carried and the most common non compliance issue that have been identified has been that of leakage radiation through the entrance of the x-ray room and behind the shielded cubicle. As part of Regulatory procedures, Inspection reports are submitted to the Licensee to address all non compliance issues. One of the major recommendations has been the use of lead to provide shielding for the entrance door, operators console and windows. It must be noted however that this recommendation has not been fully addressed by some licensees and as such the risk from the harmful effect of ionizing radiation still exists. Various reasons as to why this recommendation has not been addressed will range from the unavailability of lead in the country and the cost to acquire it from abroad and the lack of expertise in the field.

There is need however to find an alternative solution that will take into account social and economic factors. This thesis seek to propose a cost effective shielding and design of the facilities which will promote the avoidance of lead-lined entrance doors for proposed X-ray facilities.

1.3 Objectives

The main objective of this thesis is to:

1) assess the adequacy of the design and shielding of some selected general radiography imaging facilities
2) to propose alternative shielding materials for the facilities in other to promote the avoidance of lead lined doors that will achieve the highest level of radiation protection standards for workers and members of the public; and
3) Make relevant recommendations from the research findings.

1.4 Relevance and Justification

As the country continues to develop it human resource capacity in the field of Nuclear Sciences and its applications, various concerns have been raised from both the regulatory authority and other stakeholders including holders of licenses with regards to providing appropriate guidelines room design and adequate shielding specification to these facilities to ensure the highest level of protection. The sole responsibility of facility owners is to setup and implement all technical and organizational measures including provision of the required shielding, for which several efforts has been made to address this recommendation but in most cases not fully or partially achieved. Several reasons may be put forward for failure to address the recommendation. This may include lack of expert in the field, unavailability of required shielding materials such as lead. This study will be the first carried out in the country that seeks to assess the structural shielding of general radiography facilities, propose an appropriate room design or alternative shielding material that will promote the avoidance of lead lined doors and make further recommendations to research findings.

The outcome of this work will benefit policy makers, designers of x-ray facilities, licensees/registrants and the Regulatory Authority of Sierra Leone.

1.5 Scope and Limitation

This project work will be limited to assessing the structural shielding integrity of selected general radiography imaging facilities in Freetown, Sierra Leone and proposing alternative shielding materials which will promote the avoidance of the use of lead lined doors that will achieve the highest level of protection for staff and members of the public. Diagnostic Radiology shielding design can be done in different ways for which two approaches are used internationally. These approaches are The National Council on Radiation Protection and Measurements (NCRP) Report No.147 and the British Institute of Radiology (BIR) report on Radiation Shielding for Diagnostic Radiology.

The approach by the National Council on Radiation Protection and Measurements (NCRP) Report No.147 will be adopted for mathematical calculations in this study.

1.6 Organization of the thesis

This Thesis contains five chapters. Chapter one gives an introduction on the research and provides an overview of the research problem and the objectives for which the study is conducted. Chapter two provides a review of existing literature relevant to the area of research. Chapter three focuses on the materials and methodology in the framework of the study. Mathematical calculations to achieve the required results are presented and discussed in Chapter four. Chapter five contains the conclusion and recommendations from the study.

CHAPTER 2

LITERATURE REVIEW

This chapter gives a detailed review of structural radiation shielding evaluation of general radiography facilities based on NCRP 147 and BIR Methodology and shielding requirements. It also introduces the SimpleGeo tool that will be used to draw architectural floor plan of facilities and the MCNP computer code that will be used for simulation so as to achieve the objectives of this research work.

2.0 Introduction

The National Council on Radiation Protection and Measurements (NCRP) provided recommendations for the limitation of exposure to ionizing radiation in Report No. 116 These recommendations are designed to achieve the objectives of radiation protection: (1) to prevent the occurrence of clinically significant acute radiation damage and (2 to limit the risk of stochastic effects such as cancer and genetic effects. Radiation exposure to individuals from external radiation sources may be controlled and limited by any one or any combination of the following measures: (1) increasing the distance of the individual from the source (distance), (2) reducing the duration of exposure (time), and (3) using protective barriers between the individual and the source (shielding).

The purpose of shielding is to limit radiation exposure to the employees and members of the public to an acceptable level.

2.1 Overview of Shielding Design of Diagnostic Radiology Facility

The design of radiation shielding for diagnostic installation can be approached in a number of different ways. However, there are two common approaches used internationally, one based on the National Council on Radiation Protection and Measurements (NCRP) report 147 and one based on the British Institute of Radiology (BIR) report on Radiation Shielding for Diagnostic Radiology.

The basic concepts and terminology used in the design of shielding barriers include the shielding design goals, the workload for the x-ray unit, the distances to the areas to be shielded, occupancy factors for the areas to be shielded, and the use factor.

When designing new facilities the design should ensure that the doses to workers and members of the public are kept as low as reasonably achievable (the ALARA principle) taking social and economic factors into consideration. This means that the facility should be designed to ensure that the radiation exposure of workers and members of the public are much lower than those of the legal dose limits. To ensure that optimization of protection exists, dose constraints are applied to the design of any new facilities.

2.2. Siting

From a Radiation Protection Perspective, the siting, dimensions, location and structural design of facilities needs to be considered carefully and must be an integral part of the planning process based on inputs from qualified experts. Other important information such as proposed equipment type and its use, building materials that will be used for construction and occupancy factors in areas close to the proposed site are all needed during the planning stage. It should be noted also that planning takes into account ergonomic conditions. There should be adequate access to rooms for both patients and staff.

The planning of a facility should be such that it fulfills some minimum requirements;

- Patient scheduling and reception room.
- a room for patient preparation prior to radiological examination;
- image processing room (dark room);
- An image viewing area.

2.3. Room Layout

The official UK guidance on the design of radiological facilities, Health Building Note 6) suggests that general, specialized (including angiographic) and CT xray rooms should be designed to a minimum dimension of 38m^2. It is accepted that these recommended dimensions do not necessarily reflect the situation encountered in practice, where rooms may be considerably smaller.

2.4. Shielding Materials

There are different types of materials and products that can be used in providing the required radiation shielding, and the choice of materials depends on a number of factors such as the level of shielding to be achieved, the cost and availability and the practicalities of installation. The range of materials available can be divided into two distinct categories, these are; Basic materials and Fabricated Products. A choice shielding material that can be cost effective and provides adequate level of shielding can be made from the following basic materials: Lead sheet, brick, lead glass, concrete and concrete blocks, gypsum wall board, barium plaster and lead acrylic.

A range of products can also be fabricated from the basic shielding materials. These farbricated products include: wall paneling doors, frames, lead plaster board and lead glass screens.

2.5. Doors

In achieving protection in the structural design, a complete door-set is required. A typical approach will be a door which consists of a lead-lined frame and leaded stops. The design of doors must take into consideration the possibility of discontinuities at the door jamb and the door frame. On the other hand, wooden doors can also be used but unlike lead lined doors, they possess limited attenuation efficiency. There should be careful consideration if a choice of door interlock is to be made as some interlocks may interrupt x-ray production resulting in procedures being altered hence unnecessary repeat of examinations. Exception can however be made to the control room which is an essential feature of the control barrier that protects the operator.

2.6 Floors and Ceilings

The material used in the construction of floor slabs and ceilings (in storey buildings) is concrete and usually designed and specified as either standard weight or light weight concrete. High density concrete with a density of 2350kg/m^3 is a preferred choice of shielding material and may either be in the form of a poured concrete or solid concrete blocks. The attenuation properties of concrete as a shielding material depend on its thickness, density and composition. In construction, blocks may be used in combination with other materials such as barium plaster which is a gypsum plaster that incorporates barytes aggregates. However, hollow concrete blocks are not a preferred choice as a shielding material except when used in combination with other materials or in low dose/ low energy applications.

2.7 Windows

Typical unshielded window heights are 2m above from the ground outside. This approach is now not considered due to new technological developments, increased workloads. Viewing windows that are required for the control room should be large and transparent and are to be shielded from a variety of materials ranging from lead glass, lead acrylic, and plate glass and are usually marked with the lead equivalent thickness. Window frames are to have sufficient overlap between window and window frames and between window frames and wall.

2.8 Barrier Thickness

Radiation Shielding design for diagnostic radiology facilities is done by first determing the transmission requirements of the primary and secondary barriers to meet design goal and then the selection of the materials and calculating the thicknesses necessary to provide the required transmission factors.

The transmission factor (B(x)), is defined as the ratio of the air kerma beyond the barrier to the non-attenuated air kerma at the same distance (NCRP, 2004).

Barrier thicknesses are determined in terms of Tenth Value Layers (TVLs)

The number of TVLs can be determined from

$$\boldsymbol{n = -\log(B_{pri})} \tag{2.1}$$

The thickness can then be determined by the addition of the first calculated TVL with the equilibrium TVL for subsequent layers.

$$\boldsymbol{t_{barrier} = TVL_1 + (n-1)TVL_e} \tag{2.2}$$

Where

TVL_1 = first tenth value layer

TVL_e = equilibrium tenth value layer

The total barrier thickness afforded by a barrier thickness t>TVL_1 is modeled as

$$\mathbf{B= 10^{-(1+(t-TVL_1)/TVL_e)}} \tag{2.3}$$

2.9 Review of Structural Shielding Evaluation

Several approaches in determining the radiation shielding requirement have been developed and require the designer to assess both primary and secondary radiation component incident on the barrier of interest. Recommendations in the NCRP Report No.49 (NCRP, 1976) which pertains to medical diagnostic facilities were previously used. However, there were some significant fall shorts in the report as detailed in Dixon, 1994 and Simpkin, 1996.

To correct for these significant failings in the NCRP Report No.49 (NCRP, 1976), alternative methods have been developed and adopted. These are; the National Council on Radiation Protection and Measurements (NCRP) report 147and the British Institute of Radiology (BIR) report on Radiation Shielding for Diagnostic Radiology.

The NCRP and BIR approaches have important differences particularly in the shielding design goal as used in NCRP or dose constraint as used in BIR, with limitations applicable to both methodologies. The terms shielding design goal (NCRP) and dose constraint (BIR) both refer to the level of air kerma (mGy) or effective dose (mSv) that is used in calculations to ensure that annual dose limit in a specified area is not exceeded. Due to the fact that dose limits is usually given in terms of effective dose (mSv) and that effective dose(mSv) cannot be used in the calculation of shielding requirement, hence the need for the use of air kerma (mGy) in shielding calculation. This is agreed upon in both reports.

2.9.1. British Institute of Radiology Approach

The BIR approach in the calculation of primary and secondary radiation barrier requirements, recommends that one of the two methods depending on the clinical situation can be used to determine shielding requirement for primary radiation

2.9.1.1 Primary Radiation

Film dose method

This is used when the x-ray beam is intercepted entirely by the patient. The shielding calculation is based on the incident air kerma K_{inc} (mGy). The incident air kerma for the barrier under consideration is calculated using the inverse square law

$$K_{inc} = n \times K_{film} \times B_{film} \times \left[\frac{FFD}{FFD+D}\right]^{2} \tag{2.4}$$

K_{inc}= Incident air kerma

n = number of films

K_{film} = film kerma

B_{film} = transmission through film and cassette

FFD = Focus – Film distance

Primary beam attenuation is estimated based on 3 clinical geometries of exposures. These are;

(a) Table radiography

The beam is usually totally collimated and confined to a volume within the patient. Attenuation is possible in the cassette plus table. Extensive studies from Dixon's data suggest that the combined equivalence of cassette and table assembly of 60-125 kVp energy range is 0.8mm lead or 75mm concrete. This thickness will be subtracted from the required shielding calculated from the air kerma incident on the film and the limiting values of HVL.

(b) Cross-table radiography

Cross table radiography considers attenuation in the cassette only. In a situation in which the primary beam is not fully intercepted by the patient e.g in lateral skull radiography, the Entrance Surface Dose method is used from which the incident kerma will be estimated using the Inverse Square Law. The calculated shielding requirement using primary radiation transmission factors and the lead equivalence of the cassette is subtracted to give the shielding specification.

(c) Vertical bucky radiography

Vertical bucky radiography considers attenuation in the cassette plus vertical bucky.

2.9.1.2 Secondary Radiation

Secondary radiation consists of both scatter and leakage radiation. The BIR approach in dealing with scatter radiation relies on the fact that scatter kerma is a strong function of the Dose Area Product (DAP) and varies with the kVp. At different scattering angles between 115° and 120°, the maximum scatter kerma from a patient can be calculated using

$$\mathbf{S_{max} = (0.031 \times kVp + 2.5)\mu Gy\ (Gy\ cm^{2})^{-1}} \qquad (2.6)$$

S_{max} = maximum scatter factor at 1m

The scatter kerma is also proportional to the Entrance Surface Air Kerma KAP (P_{KA})

$$\mathbf{K_{scat} = S \times P_{KA}/d^{2}} \qquad (2.7)$$

K_{scat} = scatter kerma

S =

P_{KA} = Entrance Surface air kerma

d = distance from patient to boundary

The use of KAP in the determination of scatter kerma has advantages over methods that utilize a measure of workload in that

(1) No assumption for field size is required

(2) The KAP value is measured after filtration

The incident air kerma K_{inc} (μGy) for scattered radiation is calculated from

$$\boldsymbol{K_{inc} = \frac{S_{max} \times DAP}{d^2}} \quad (2.8)$$

K_{inc} = incident air kerma

S_{max} = maximum scatter factor at 1m

DAP = weekly Dose Air Product

d = distance from patient to boundary

Following the calculation for the incident air kerma K_{inc} (μGy), the maximum allowable transmission (B) based on the annual dose limit must be determined. This is given by

$$\boldsymbol{B = \frac{D_c}{K_{inc} \times T \times 52}} \quad (2.9)$$

B = maximum allowable transmission

D_c = annual dose constraint

K_{inc} = incident kerma on boundary per week

T = occupancy factor for adjoining area

However, if additional shielding is required, the maximum allowable transmission B will be less than 1. If B equals 1 or greater no additional shielding will be required.

In order to determine the thickness of material if additional shielding is required, the following expression can be used.

$$\boldsymbol{x} = \frac{\mathbf{1}}{\alpha\gamma} \boldsymbol{ln} \left[\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \tag{2.10}$$

$\boldsymbol{x}$ = thickness of material required

$\boldsymbol{\alpha\beta\gamma}$ = fitting parameters

$\boldsymbol{B}$ = Broad Beam Transmission

2.9.1.3 Combination of Primary and Secondary Radiation

In situation where the barrier to be assessed is exposed to both primary and secondary radiation, The BIR recommends that the annual dose limit should be halved and the constraint value be used in calculating shielding requirement for both primary and secondary radiation. It should be assumed also that the primary component dominates and secondary radiation can be ignored. The sum of primary and secondary transmissions should be less than 1.0mGy per annum.

2.9.2 National Council on Radiation Protection and Measurement Approach

A convenient way to use the NCRP method is by use of tabulated data on workload distributions, unshielded air kerma, use factors, equivalent thickness of pre shielding materials, occupancy factors, transmission curves, fitting parameters for broad beam transmission of both primary and secondary radiation found in the report (NCRP147).

The method also considers the three components of radiation (primary, leakage and scatter) separately.

2.9.2.1 Primary Barrier

Computation of primary barrier shielding requires knowledge of six basic parameters. These are;

P =The level in mSv to which radiation exposure in an adjacent occupied area must be reduced.

dp =Distance in meters from source to area being protected.

W =Workload or Workload Distribution expressed in mA min per wk

U =Use Factor: the percentage of time the source of radiation is incident on the barrier

T= Occupancy Factor: the percentage of time the area is occupied

kVp = The operating potential of the x-ray producing equipment

The NCRP approach in the calculation of primary barrier shielding requirement follows Simkin and Dixon's method.

The method considers the unattenanted primary air kerma from a soure due to the given workload to be

$$K_p^1\,(kVp) = K_w^1\,(kVp)\,W(kVp) \qquad (2.11)$$

At a given distance d_p from the focal spot, the untenanted primary air kerma is given as

$$K_p^1\,(kVp) = \frac{K_w^1\,(kVp)\,W(kVp)}{d_p^2} \qquad (2.12)$$

If the occupied area is shielded by a materials of thickness x, with primary transmission Bp (x, kvp) at the operating potential, it follows that

$$\mathbf{K_p^1\,(kVp)} = \frac{\mathbf{K_w^1\,(kVp)W(kVp)}}{\mathbf{d_p^2}}\mathbf{B_p(x, kVp)} \qquad (2.13)$$

Assuming that the workload is distributed such that a fraction is directed towards a particular barrier, the unattenuated primary beam to the occupied area will be reduce by U. therefore,

$$\mathbf{K_p^1\,(kVp)} = \frac{\mathbf{K_w^1\,(kVp)UW(kVp)}}{\mathbf{d_p^2}}\mathbf{B_p(x, kVp)} \qquad (2.14)$$

$\mathbf{K_w^1}$ values were obtained from the data of Archer et al. (1994) (W anode/Al filtered radiography tube)

$$\mathbf{Air\ Kerma = 1.222 - 5.664 \times 10^{-2}\ kVp + 1.227 \times 10^{-3} kVp^2 - 3.136 \times 10^{-6} kVp^3} \qquad (2.15)$$

For a given x-ray tube, the total workload W_{tot} due to N number of patients is

$$\mathbf{W_{tot} = NW_{norm}} \qquad (2.16)$$

W_{norm} = normalized workload

From which

$$N = \frac{W_{tot}}{W_{norm}} \qquad (2.17)$$

The sum of the unshielded primary air kerma at all operating potential will then be

$$K_P(x_{tot}) = \sum_{kVp} K_p(x_{tot}, kVp) = \sum_{kVp} \frac{K_w^1(kVp)UW(kVp)}{d_p^2}\, B_p(x_{tot}, kVp) \qquad (2.18)$$

Assuming that $x_{tot} = 0$ and from (2.11) and (2.16)

If follows that, the weekly primary air kerma in the occupied area due to N number of patients is given by

$$K_p(0) = \frac{K_p^1 \times N \times U}{d_p^2} \qquad (2.19)$$

For an acceptable barrier thickness $x_{barrier}$ the unattenuated primary air kerma will reduce to the shielding design goal i.e $\frac{P}{T}$

From (2.14) and (2.17)

$$\frac{P}{T} = B_P(x_{barrier})\frac{K_p^1 \times N \times U}{d_p^2}$$

From which (2.20)

$$B_P(x_{barrier}) = \frac{Pd_p^2}{K_p^1 NUT}$$

2.10 Distance to the Occupied Area

The intensity of radiation is significantly reduced with distance. It is important to decide if maximizing distances will reduce radiation levels and hence allocation of space, or by installation of adequate shielding. The source of primary radiation is the X-ray tube and the main source of scatter is the patient and as such, measurements will be taken at the distance from the tube to the organs of interest of the occupant nearest to the boundary in question. For a wall transmission, this distance will not be less than 0.3m. If the tube is located above occupied spaces, the required distance from the sensitive organs of occupants below will not be greater than 1.7m. For transmission through ceiling, the required distance is at least 0.5m. The distances adopted are shown in Table 4.4 (Based on NCRP, 2004

Table 2 1: Minimum distance to the sensitive organ of a person in the adjoining area

Boundary	Minimum distance to occupants in Occupied Area
Walls	0.3m
Ceilings	0.5m from above floor
Floors	1.7m from floor below

2.11 Occupancy Factor (T)

This factor is realistically considered as the fraction of time in an occupied area spent by a maximally exposed individual who is most likely a member of staff while the x-ray beam is on.

Table 2 2: suggested occupancy factor (for use as a guide in planning shielding where other occupancy data are not available). NCRP147

Location	Occupancy Factor
"Administrative or clerical offices, laboratories, pharmacies and other work areas fully occupied by an individual; receptionist areas, children's indoor play areas, adjacent x-ray rooms, film reading areas, nurse's stations, x-ray control rooms	1
Rooms used for patient examination and treatment	1/2
Corridors, patients rooms, employee lounges, staff rest rooms	1/5
Corridor doors	1/8
Public toilets, unattended vending areas, storage rooms, outdoor areas with seating, unattended waiting rooms, patient holding areas	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas, attics, stairways, unattended elevators, janitors closet"	1/40

2.12 Use Factor (U)

This is considered as the fraction of the workload of the x-ray unit for which the primary beam is directed towards a particular direction or an occupied area. Use Factor values are dependent on the type of facility and the barrier that is of concern.

Table 2 3: Primary beam use factors (U) for a general radiographic room determined from a survey of clinical sites

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)
Chest Image Receptor	1.00	Rad Room (chest bucky)

2.13 Secondary Barrier (NCRP Approach)

2.13.1 Scattered Radiation

Scattered Radiation are radiation that is scattered from a patient and the intensity depends on the angle of scatter i.e direction of the center of primary beam to a ray pointing to the occupied area, the primary beam photon energy, the location of the x-ray beam on the patient and the number of primary beam incident on the patient.

An assumption is made that the number of primary photons incident on the patient varies linearly with the x-ray beam field size such that for a fixed kVp, mAs, the scattered radiation intensity is dependent on the distance from the primary x-ray source to the patient.

Trout and Kelly (1972) made a series of scattered radiation measurements at 100cm from the center of a phantom which was then related to the primary air kerma at 1m. The ratio of the scattered to primary air kerma was divided by the primary beam field size at a primary distance of 1m and this defines the scatter fraction (a_1). Due to modernization, the filtration of the x-ray beam used by Trout and Kelly (1972) at 50 and 70kVp are not typical of x-ray systems used today. Measurements were repeated by Dixon (1994) for 90 degrees scatter over a range of operating potentials for which the results indicate a linear increase in a_1 with kVp and as such invalidated the results of Trout and Kelly (1972) at these lower potentials.

The unshielded air kerma of the scaled factor a_1 at scattering angle θ, at 1m from the center of the patient due to scattered radiation is

$$\boldsymbol{K_s(\theta, kVp) = K_P^1(kVp) a_1(\theta, kVp) \times 10^{-6}} \qquad (2.21)$$

The scatter fraction $a_1(\theta, kVp) \times 10^{-6}$ are obtained from data of Trout and Kelley (1972) and reanalyzed by Simpkin and Dixon (1998) for tungsten anode, aluminum-filtered beams. It is given by the relation

$$\boldsymbol{a_1(\theta, kVp) = 1.6 \times 10^{-2}\,(kVp-125) + 8.43 - 1.11\times10^{-1}\times \theta + 9.83\times10^{-4}\,\theta^2 - 1.74\times10^{-6}\times\theta^3}$$

(2.22)

As stated above, it is assumed that the scattered air kerma scales linearly with the primary x-ray beam area. If the primary beam area size is F at primary radiation distance d_f (m) and the scatter radiation distance from the center of the patient is d_s (m), the unshielded scattered air kerma K$_s$ (θ, kVp) at the scattered radiation distance d$_s$ from the patient is given by

$$K_s\,(\theta, kVp) = \frac{K_P^1(kVp)a_1(\theta, kVp) \times 10^{-6}}{d_s^2}\frac{F}{d_f^2} \qquad (2.23)$$

The scattered air kerma behind a shielded barrier of thickness *x* having a transmission B(*x*, kVp) is

$$K_s\,(x, \theta, kVp)$$

$$= \frac{K_w^1(kVp)W(kVp)a_1(\theta, kVp) \times 10^{-6}}{d_s^2}\frac{F}{d_f^2}\;\; B(x, kVp) \qquad (2.24)$$

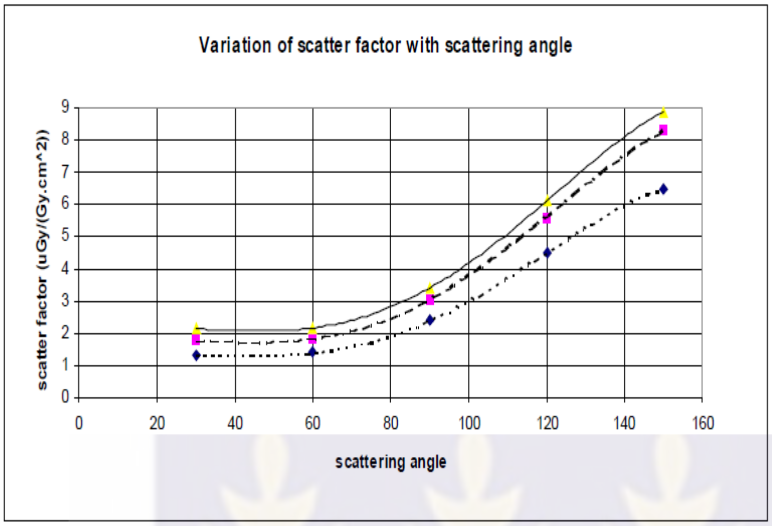
If a fraction U of the x-ray tube workload is expended as a primary beam directed at this barrier, the workload available to generate scattered radiation on this barrier should be reduced from W(kVp) to (1-U)W(kVp) (Simpkin, 1987). Then:

$$K\_(s\,)(x, \theta, kVp)$$

$$= \frac{K_w^1(kVp)(1-U)W(kVp)\quad a_1(\theta, kVp) \times 10^{-6}}{d_s^2}\frac{F}{d_f^2}\;\; B(x, kVp) \qquad (2.25)$$

For a range of operating potential, the total scattered air kerma is the sum over the operating potentials;

$$K_s = \sum\nolimits_{kVp} K_s\,(x, \theta, kVp) \qquad (2.26)$$



——— 105kVp --------85kVp ……….50kVp

Fig 2 1: Variation of scatter factor with scattering angle

Ref: The Shielding of Radiographic facilities at diagnostic energies. Shielding design for diagnostic x-ray rooms draft of June 1999.

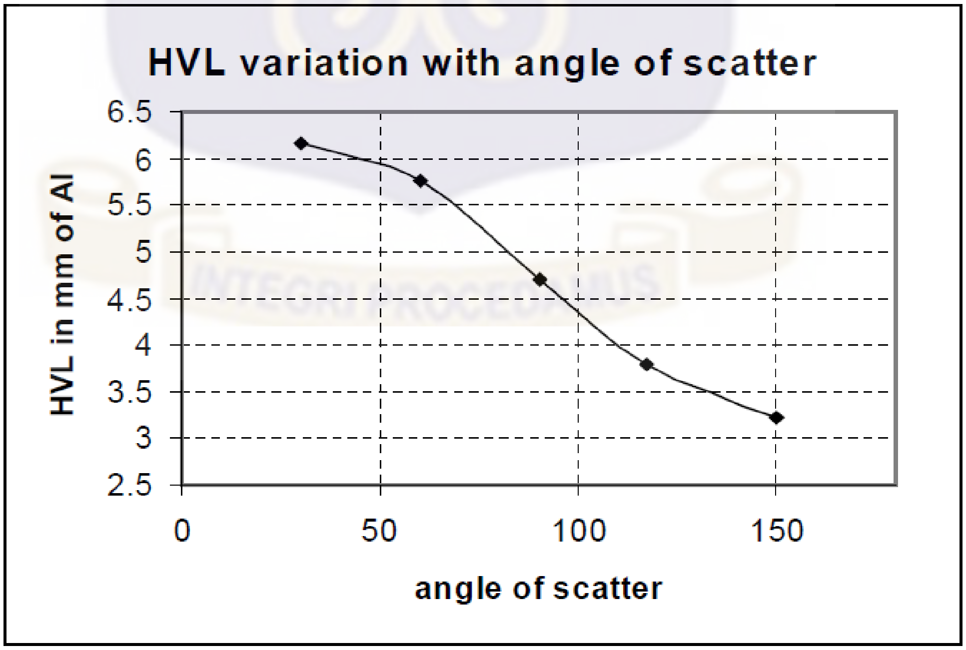


Fig 2 2: Variation of HVL and angle of scatter

Ref: The Shielding of Radiographic facilities at diagnostic energies. Shielding design for diagnostic x-ray rooms draft of June 1999.

2.13.2 Leakage Radiation

Leakage Radiation is limited by regulation to 100mRh^{-1} at 1m at the maximum kVp and maximum tube current that the tube can be operated continuously. The radiation that is transmitted through the tube housing is considered much more penetrating than the primary or scattered radiation and is therefore characterized by the half value layer (HVL) in a material at high attenuation.

The leakage air kerma rate at 1m from the x-ray tube operated at a given potential kVp and tube current I is given by

$$\dot{K}_L(kVp) \propto kVp^2 I\, B_{housing}(kVp) \qquad (2.27)$$

The ratio of the leakage air-kerma rates at 1m at clinical parameters kVp and I to that at the maximum values of the leakage radiation technique factors gives

$$\dot{K}_L(kVp) = \frac{K_{lm} kVp^2 B_{housing}(kVp) I}{kVp^2 B_{housing}(kVp) I_{max}} \qquad (2.28)$$

Equation (2.24) assumes the highest allowed air kerma rate at leakage radiation technique factors.

For an area located at the leakage radiation distance d$_L$ from the x-ray tube, the transmission of leakage radiation through a shielding barrier of thickness *x* will be

$$e\left[-(\ln 2)\,{}^{x}\!/_{x_{\frac{1}{2}}}(kVp)\right]$$

Where

$x_{\frac{1}{2}}(kVp)$ = HVL through the barrier material at high attenuation.

If a fraction U of the x-ray tube workload is expended as a primary beam directed at this barrier, the workload available to generate leakage radiation on this barrier should be reduced from W(kVp) to (1-U)W(kVp) (Simpkin, 1987). Then the leakage air kerma to this shielded are will be

$$\boldsymbol{K_L(\dot{k}Vp) = \frac{K_{lim}kVp^2B_{housing}(\dot{k}Vp)(1-U)W(kVp)}{kVp^2B_{housing}(kVp)I_{max}} \frac{e^{-(ln2)x}}{x_{\frac{1}{2}}(kVp)} / d_L^2} \qquad \textbf{(2.29)}$$

For a range of operating potential, the total leakage air kerma is the sum over the operating potentials

$$\boldsymbol{K_L(x, kVp)} = \textstyle\sum_{\boldsymbol{kVp}} \boldsymbol{K_L(x, kVp)} \qquad (2.30)$$

2.14 Overview of Monte Carlo N-Particle

MCNP is a general-purpose, continuous-energy, generalized-geometry, time-dependent Monte Carlo transport code that is used in several transport modes. It has energy range for neutrons from 10 -11 MeV, 20 MeV for all isotopes and up to 150 MeV for some isotopes, photon energy range from 1 keV to 100 GeV, and electron energy range from 1 KeV to 1 GeV.

An input file which is created by the user is subsequently read by MCNP. The input file contains information on

- the geometry specification,

- the description of materials and selection of cross-section evaluations,
- the location and characteristics of the neutron, photon, or electron source,
- the type of answers or tallies desired, and
- any variance reduction techniques used to improve efficiency

2.15 Monte Carlo Method and Deterministic Method

Monte Carlo methods are very different from deterministic transport methods in that Monte Carlo obtains answers by the simulation of individual particles and records the average behaviors of some aspects (tallies). Deterministic methods, the most common of which is the discrete ordinates method, solve the transport equation for the average particle behavior.

2.16 The Monte Carlo Method

Monte Carlo can be utilized to duplicate statistical process theoretically and solving complex problems that cannot be modeled by computer codes that use deterministic methods. The simulation is done on a digital computer to accommodate the number of trials necessary to describe the phenomenon that is usually quite large.

2.17 Introduction to Features of MCNP

2.17.1 Nuclear Data and Reactions

The primary sources of nuclear data are evaluations from the Evaluated Nuclear Data File (ENDF) system, Advanced Computational Technology Initiative (ACTI), the Evaluated Nuclear Data Library (ENDL), Evaluated Photon Data Library (EPDL), the Activation Library (ACTL) compilations from Livermore, and evaluations from the Nuclear Physics (T–16) Group at Los Alamos. Evaluated data are processed into a format appropriate for MCNP by codes such as NJOY.

2.17.2 Tallies and Output

MCNP, upon instructions from the user makes various tallies related to particle current which is a function of direction across the surface or a surface segment, particle flux tallied on a mesh superimposed on the geometry, across any set of surfaces, surface segments, sum of surfaces, and in cells, cell segments. The tallies are considered to be per starting particle except for a few special cases with criticality sources.

2.17.3 Estimation of Monte Carlo Errors

As stated earlier, MCNP tallies are per starting particle that are accompanied by a second number R in the output , which is the estimated relative error. The quantities required for this error estimates the tally and its second moment and compute them after each complete Monte Carlo history. For a well-behaved tally, *R* will be proportional to 1 / √N.

Thus, to halve *R*, the total number of histories must be increased fourfold. For a poorly behaved tally, R may increase as the number of histories increases [23].

2.17.4 Variance Reduction

R is proportional to 1/ √N. For a given MCNP run, the computer time T consumed is proportional to N. Thus, R= C/√T,

and C depends on the tally. R can be reduced in a number of ways

(1) increase T

(2) decrease C.

MCNP has special variance reduction techniques for decreasing C. (Variance is the square of the standard deviation.).

2.18 Particle Interaction Processes by MCNP

There are 4 interaction processes that can be modeled by photon Monte Carlo Code.

2.18.1 Pair Production in the nuclear field

A photon interacts with the nucleus; annihilate to produce an electron-positron pair. A third body, usually a nucleus, is required to be present for the conservation of energy and momentum. Materials containing high atomic number converts photons into charged particles than those with low atomic number materials. Pair production interaction gives rise to charged particles in the form of electrons and positrons (muons at very high energy) and the bremsstrahlung interaction of the electrons and positrons leads to more photons.

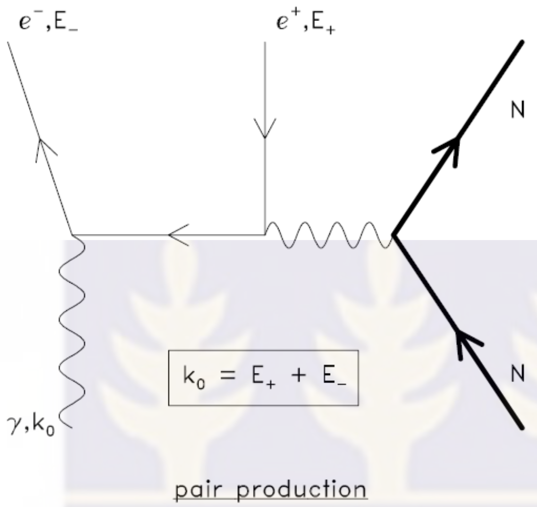


Fig 2 3: Feynman diagram depicting pair production in the field of a nucleus

2.18.2 Compton Interaction (Incoherent Scattering)

The Compton interaction is an inelastic “bounce” of a photon from an electron in the atomic shell of a nucleus. It is also known as “incoherent” scattering in recognition of the fact that the recoil photon is reduced in energy.

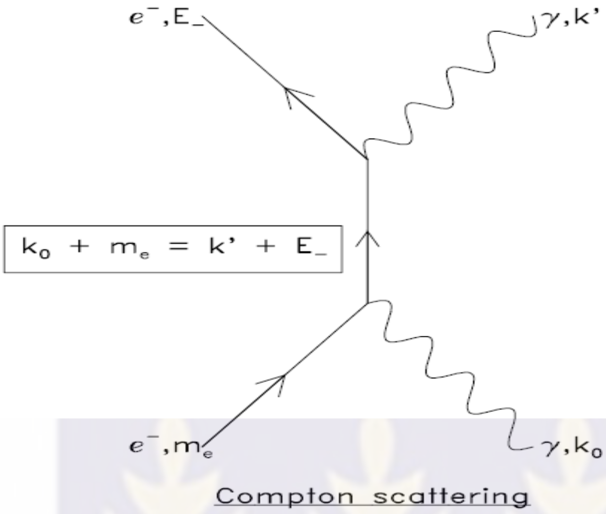


Fig 2 4: Feynman diagram depicting Compton scattering in free space

2.18.3 Photo electric interaction

The dominant low energy photon process is the photoelectric effect. In this case the photon gets absorbed by an electron of an atom resulting in escape of the electron from the atom and accompanying small energy photons as the electron cloud of the atom settles into its ground state.

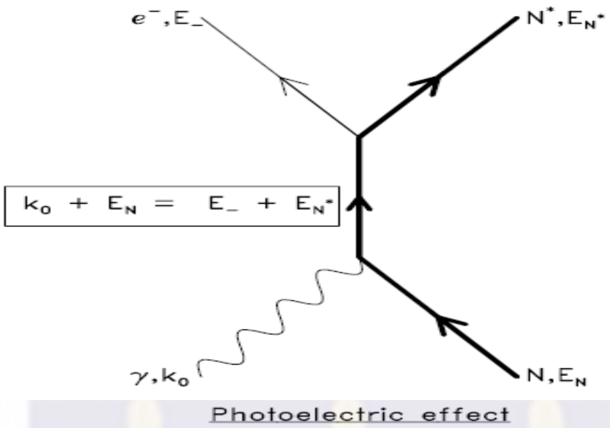


Fig 2 5: Photoelectric effect

2.18.4 Rayleigh Interaction (coherent scattering)

In terms of cross section, the Rayleigh cross section , also known as coherent scattering section is at least an order of magnitude less that the photoelectric cross section. The distinguishing feature of this interaction in contrast to the photoelectric interaction is that there is a photon in the final state. If low energy photons impinge on an optically thick shield both Compton and Rayleigh scattered photons will emerge from the far side. Moreover, the proportions will be a sensitive function of the incoming energy. The coherent interaction is an *elastic* (no energy loss) scattering from atoms.

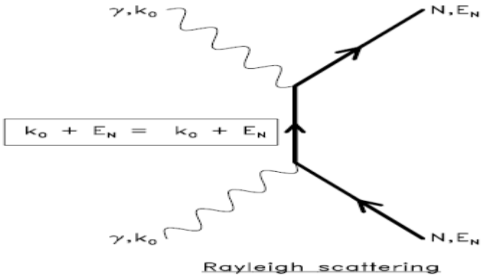


Fig 2 6: Rayleigh scattering

2.19 Photon Tracking during Monte Carlo Simulation

Photon transport used here is simplified by ignoring electron creation and considering that the transport occurs in only a single volume element and a single medium. Assuming that an initial photon's parameters are present at the top of an array called STACK and that there is a photon transport cut off defined. STACK is an array that retains particle phase space characteristics for processing.

Photons that fall below this cutoff are absorbed "on the spot". However, they do not contribute significantly to any tallies of interest and can be ignored.

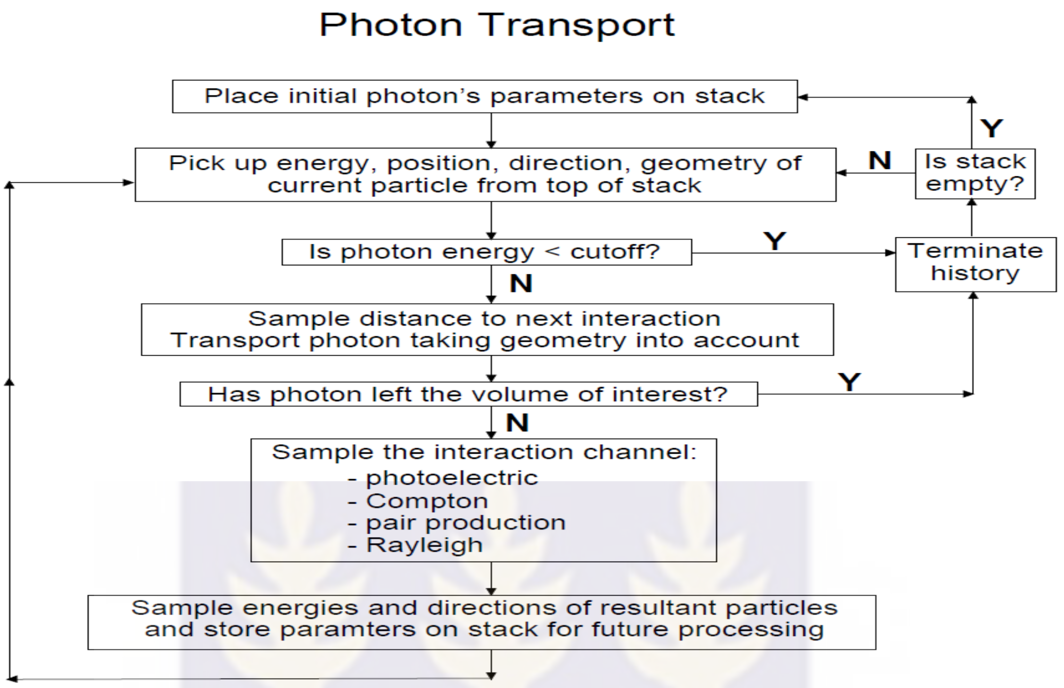


Fig 2 7: Photon Transport

2.20 Creating an MCNP Input File

An input file which is readable and can be interpreted by MCNP is created by the user. The file name cannot exceed 8 characters. The default name is “INP”. INP contains:

- Geometry specification
- Description of materials
- Choice of cross-section tables
- Source characterization
- Type of answers desired
- Variance reduction techniques desired

Format of input file: Title Line (also called Title "Card"); Several lines describing cells (3D volumes) making up the system; (blank line); Several lines describing the surfaces used to make up the cells; (Blank line); Data lines describing source, materials, detectors, and problem control.

2.20.1 INP File: Geometry Specification

Specify in 3D – source of particles, medium of interaction, and location of measurement. The entire geometry is made up of surfaces [Planes, spheres, cones, ellipses, etc.]. The surfaces are combined using Boolean algebra to form closed "cells". The bound 3D volumes of various shapes are indicated. Each cell must be assigned a material number and a density.

2.20.2 Cell Cards

The format for the cell cards are in the following sequence: cell #, material#, +/-material density, surfaces importance. Example: 1 1 -1.04 -100 200 imp:n = 1 [34].

2.20.3 Surface Cards

Surfaces are used to bound regions of space and for specification of tallies. The format for the surface cards are in the following sequence: surface #, mnemonic, mnemonic entries. The surfaces are combined, using AND, OR or complement operators to define 3D bounded volumes. Intersections are indicated by a blank space; unions are indicated by a colon (:), and complements indicated by # [34].

2.20.4 INP file: Description of Materials

A material is specified for each cell with the material card specifying both the elemental and the isotopic composition of one material. It is in the form: Material # ZZZAAA.nnX_1 fraction$_1$ ZZZAAA.nnX_2 fraction$_2$ etc. ZZZAAA.nnX is the identifier for that particular isotope where ZZZ is the atomic number, AAA is the atomic mass, nn is the library identifier, and X is the class of data. For naturally occurring elements, AAA=000.

2.20.5 INP File: Source Definition (Sdef)

Sdef card specifies spatial, energy and angular dependencies. The type of particle is defined by Mode N, Mode P, or Mode E to initiate neutrons, photons or electrons. The user can also specify Mode N, P which will initiate neutrons but track both neutrons and induced photons, or Mode N P E which will also track the secondary electrons produced in photon interactions following photon production via (n,γ) interactions.

2.20.6 INP File: Tallies

The tallies are the desired answers from the INP file and they come in the following forms: "F1:n,p,e Surface Current; F2:n,p,e surface Flux; F4:n,p,e Track Length Estimation (Volume averaged flux); F5:n,p,e Point or Ring Detector; F6:n,p,e Track Length Estimation of Energy Deposition; F7:n,p,e Track Length Fission Energy Deposition; F8:n,p,e Pulse Height Tally".

2.21 Theory on SpekCalc

SpekCalc is an executable for calculating the x-ray emission spectra from tungsten anodes, such as those used in diagnostic radiology and kV radiotherapy x-ray tubes.

The theoretical approach underlying SpekCalc combines elements of two approaches. The survival probabilities for an electron reaching certain depths within the target and the electron energy distributions at those depths. SpekCalc is computationally very fast with small program and data (a single 6 MB executable and a few data files).

2.22 Geometric modelling of SimpleGeo

2.22. 1. Computer aided design

Computer Aided Design (CAD) packages is a common tool in the field of engineering. These packages include either an explicit support for solids or a rigid body is represented by its boundary faces, made up of connected edges. Curved surfaces can be approximated by patches of planar faces or, if available, using free-form surfaces like non-uniform rational B-splines.

2.22.2. Hierarchical constructive solid geometry

Hierarchical CSG is a modeling scheme that represents 3D solids by a tree-graph whose leaves contain geometric primitives and nodes represent Boolean and affine operations. The analytic descriptions used, makes this approach much more suitable in creating the geometries for radiation transport simulations because efficiency and consistency problems are inherently avoided. Modeling operations include (1) instantiation of basic primitives, (2) creation of complex models made of basic primitives in a hierarchical way, using Boolean operations (union, difference, intersection), (3) application of affine operations (translation, rotation, scaling) [43].

CHAPTER 3

MATERIAL AND METHODS

The methodology adopted by the NCRP for assessing the shielding adequacy of diagnostic radiology facilities are presented in this chapter. The use of SimpleGeo tool kit to develop a three dimensional image of the architectural plans of all the facilities considered for the study and simulation using Monte Carlo N-Particle 6 (MCNP6) are also outlined in this chapter.

3.1 MATERIALS

Two (2) RADOS dose rate meters calibrated at the Secondary Standards Laboratory (SSDL) at the Radiation Protection Institute of the Ghana Atomic Energy Commission (GAEC) were used to measure dose rate in and around the facilities at specified locations. A DIADOS E diagnostic dose meter which measures the “dose, dose rate, irradiation time, dose/pulse, pulses” was used to measure the dose at different kVp at varying distance from the x-ray tube, and the values obtained were used to verify the computational models. Measuring Tape was used to for measurements of x-room.. Drawing tools from Microsoft Word used to draw the floor plan of all the facilities considered for the study.

Monte Carlo N-Particle (MCNP) code: used to track the x-ray transport in the x-ray room to investigate the shielding and design integrity. Lastly, SimpleGeo is a computational software used to model three (3) dimensional images of the x-ray facilities.

3.2 METHODS

3. 2.1 Data on the X-ray Facilities

Data was collected from 5 x-ray facilities in Freetown, Sierra Leone . Data sheets were used to collect the following:

- Floor plan
- Machine and its specification
- Machine location / tube orientation
- Room size
- Distance from tube to examination table, chest bucky, control panel, barriers, and entrance door
- Status of barriers
- Status of the entrance door

3.3 Estimation of Workload

3.3.1 Determination of the kVp workload distribution.

The kVp, mAs and number of procedures were collected with a data sheet. Each mAs value was divided by 60 to convert it to mAmin for which the workload per procedure was calculated. The mAs values were grouped with the corresponding kVp in a given interval of five (5) i.e 50kVp, 55kVp, 60kVp etc. divided by the number of procedures. The sum of the kVp distribution gives the normalized workload per patient for the facility.

3.3.2. Determination of the Unshielded Primary air kerma per Patient (K_p^1)

The air kerma at 1m per unit workload due to the primary beam (K_w^1) was first determined from equation (2.15). Each K_w^1 was then multiplied by the W(kVp) distribution. The sum of the K_w^1. W(kVp) equation (2.11) gives the unshielded primary air kerma (K_p^1)

3.4 Determination of the Use Factor (U)

The use factor for barriers in the facility is obtained by dividing Normalized workload per patient for the barrier under consideration by the normalized workload per patient for all barriers

3.5 Determination of the Distance to the occupied area

The distance to the occupied area was measured from the focal spot of the x-ray tube to the (primary barrier) chest bucky + 0.3m beyond the barrier (for walls) + thickness of barrier (all measurement in mm).

In the case of floors and ceiling, measurements were taken from the focal spot + 0.5m (above the floor) + floor thickness or 1.7m (from floor below) + thickness.

3.6 Transmission factor calculation

3.6.1 Primary barrier transmission

The transmission factor for the primary barrier was obtained from the relation

$$B_{x(barrier)} = P/K_p(0) \qquad 3.1$$

3.7 Determination of Primary Barrier shielding thickness

Shielding calculations are aimed at determining the barrier thickness that will provide the attenuation of the primary beam so as to reduce the air kerma to the occupied area to a value that is less than the weekly shielding design goal P, modified by the occupancy factor.

The first step in determining a given primary barrier shielding requirement is to calculate the weekly unshielded primary air kerma to the occupied area. This is given by

$$K_p(0) = K_p^1 \; UN \div d_p^2 \qquad (3.2)$$

$K_p(0)$ = weekly unshielded primary air kerma at a distance due to N number of patients

K_p^1 = unshielded primary air kerma per patient at 1m calculated for a workload distribution of total workload per patient W_{norm}

U = use factor

N = number of patients undergoing examination in a given room

d_p^2= distance travelled by primary beam from x-ray tube to the occupied area.

With the value obtained from *equation 3.2* unshielded primary air kerma, the required barrier transmission factor is determined from

$$\mathbf{B}_{(xbarrier+xpre)} = (\mathbf{P}/\mathbf{T})\mathbf{d}_p^2 \,/\mathbf{K}_p^1\,\mathbf{UN} \qquad (\;3.3\;)$$

Broad beam transmission function $\mathbf{B_x}$ is the ratio air kerma behind a barrier of given thickness x to the air kerma at the same location with no barrier. Attenuation curves for different shielding materials will then be utilised to determine the required thickness for a given workload distribution.

However, the image receptor in any given examination provides some form of attenuation or pre filtration of the primary beam that can be compared to a given thickness of the existing pre shielding material.

Table 3 1: Equivalent thickness of primary beam pre shielding (Dixon, 1994)

Application	**X_{pre} (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)	0.3	30	2

The x_{pre} value of the given shielding material will then be subtracted from the already determined attenuation curve value for the required shielding material to obtain the actual thickness of barrier.

An alternative solution to determine primary barrier thickness is to consider the required thickness of material to be a function of, or dependent on

$$\frac{NT}{Pd^2} \tag{3.4}$$

N = number of patients

T = occupancy factor

P= shielding design goal

d= distance to the occupied area

This is so if we critically examine **equation 3.3** which show an apparent dependence on $\frac{NT}{Pd^2}$ in determine the required shielding thickness for a given primary barrier.

Considering the fact that determination of the transmission of x-rays through a given material is quite a daunting task, in that the transmission occurs under broad beam condition and the spectrum of the x-rays is polyenergetic, a further study was done by Archer et al. (1983) for which a model that will achieve a more algebraic solution in determining the required primary barrier thickness was proposed

$$x_{barrier} = \frac{1}{\alpha\gamma} ln \left[\left(\frac{NTU\,K_p^1}{pd_p^2} \right) \; ^{\gamma} + \frac{\beta}{\alpha} \quad 1 + \frac{\beta}{\alpha} \right] - x_{pre} \qquad (3.5)$$

$x_{barrier}$ = thickness of barrier material that decreases air kerma in occupied area to the appropriate shielding design goal

$x_{pre=}$ thickness of “preshielding” material that intercepts the primary beam

K_p^1 = unshielded primary air kerma per patient at 1m calculated for a workload distribution of total workload per patient W_{norm}

α, β,γ = fitting parmeters

N = number of patients undergoing examination in a given room

T = occupancy factor

U = use factor

The approaches or methods discussed so far for primary barrier shielding requirement can be applied for both barriers containing the chest bucky and the floor.

3.8 Determination of Secondary Barrier shielding thickness

As earlier indicated, secondary radiation is radiation consisting of both scatter radiation which is a result of scattered photons off the patients and any other object in the path of the primary beam and leakage radiation generated at the tube and transmitted through the tube housing. The secondary barrier is aimed at reducing the air kerma from the scattered and leakage component to the shielding design goal, P.

For the purpose of this research, the facilities under evaluation are such that the tube orientation is directed at the chest bucky and over table exposure examination. Therefore, shielding calculations was done for all barriers on which secondary radiation resulting from examination for both chest bucky and over table will impinge on.

3.8.1 Determination of unshielded secondary air kerma

The first step for any given barrier or occupied area is the determination of the unshielded secondary air kerma to the occupied area.

The unshielded secondary air kerma (scatter + leakage) was determined from equation (2.25), (2.29) and (2.30)

$$K_{sec}\ (0) = K_{sec}^{1}\ N/d_s^2 \qquad (3.6)$$

Equation 3.6 was used to calculate for the scattered component resulting frond chest bucky examination and scatter and leakage component resulting from over table exposures. Since secondary radiation consists of scatter and leakage component, the results from equation 3.6 will give the total unshielded from secondary air kerma to the barrier of interest or the occupied area.

$\boldsymbol{K_{sec}\,(0) = K^1_{sec}\; N/d^2_s}$ **(chest bucky component scatter) +** $\boldsymbol{K^1_{sec}\; N/d^2_L}$ **(tube component leakage)** (3.7)

The value obtained in equation 3.7 was used to determine the barrier transmission factor using equation 3.8

$$B_{\sec\left(x_{barrier}\right)} = \left(\frac{P}{T}\right) d^2_{sec} / K^1_{sec} N \tag{3.8}$$

The barrier thickness $\boldsymbol{x_{barrier}}$ in equation 3.8 can be determined graphically through transmission curves.

As in the case of primary barriers shielding requirement, an algebraic solution formulated by Archer et al. (1983), can also be used in determining the secondary barrier requirement$\boldsymbol{x_{barrier}}$.

Archer's model is in the form

$$\boldsymbol{B = \left[\left(1 + \frac{\beta}{\alpha}\right) e^{\alpha\gamma x} \; - \frac{\beta}{\alpha}\right] \quad ^{-\frac{1}{\gamma}}} \tag{3.9}$$

solving equation (3.9) for x as a function of B, yields

$$\boldsymbol{x = \frac{1}{\alpha\gamma}\, ln\left[B^{-\gamma} \; + \frac{\beta}{\alpha} \;\; \div\, 1 + \frac{\beta}{\alpha}\;\right]} \tag{3.10}$$

Substituting the value B_{sec (xbarrier)} from equation (3.8) into equation (3.10) will yield

$$x_{barrier} = \frac{1}{\alpha\gamma} ln\left[\left(NTK^1_{sec}\right) \;\; \gamma\right] + \frac{\beta}{\alpha} \div 1 + \frac{\beta}{\alpha} \tag{3.11}$$

3.9. MONTE CARLO SIMULATION

3.9.1 Three Dimensional Modeling

The architectural floor plan of the room was drawn using a three dimensional modeling tool known as SimpleGeo. Measuring tape was used to take the detailed dimensions of the x-ray room size, control room size, wall thicknesses, room height, the position of the x-ray tube with respect to the room, the patient couch and door thicknesses. The material compositions of all the measured components were noted as well. SimpleGeo was used to model the x-ray room, control room, couch, perspex phantom and x-ray tube using the detailed measurements taken. A semiconductor detector was modeled as well positioned at the places of interest using specifications from literature. The semiconductor detectors were positioned before and after all doors leading to the x-ray room, wall A, wall B, wall C, wall D and the control room shielding barriers. The modeling process is as shown in Figure 3.1. The material composition of all the component part of the model is identified in SimpleGeo and saved. The saved model is then processed or converted into a Monte Carlo input file for simulation. This process is repeated for all the identified facilities (hospitals) for the study.

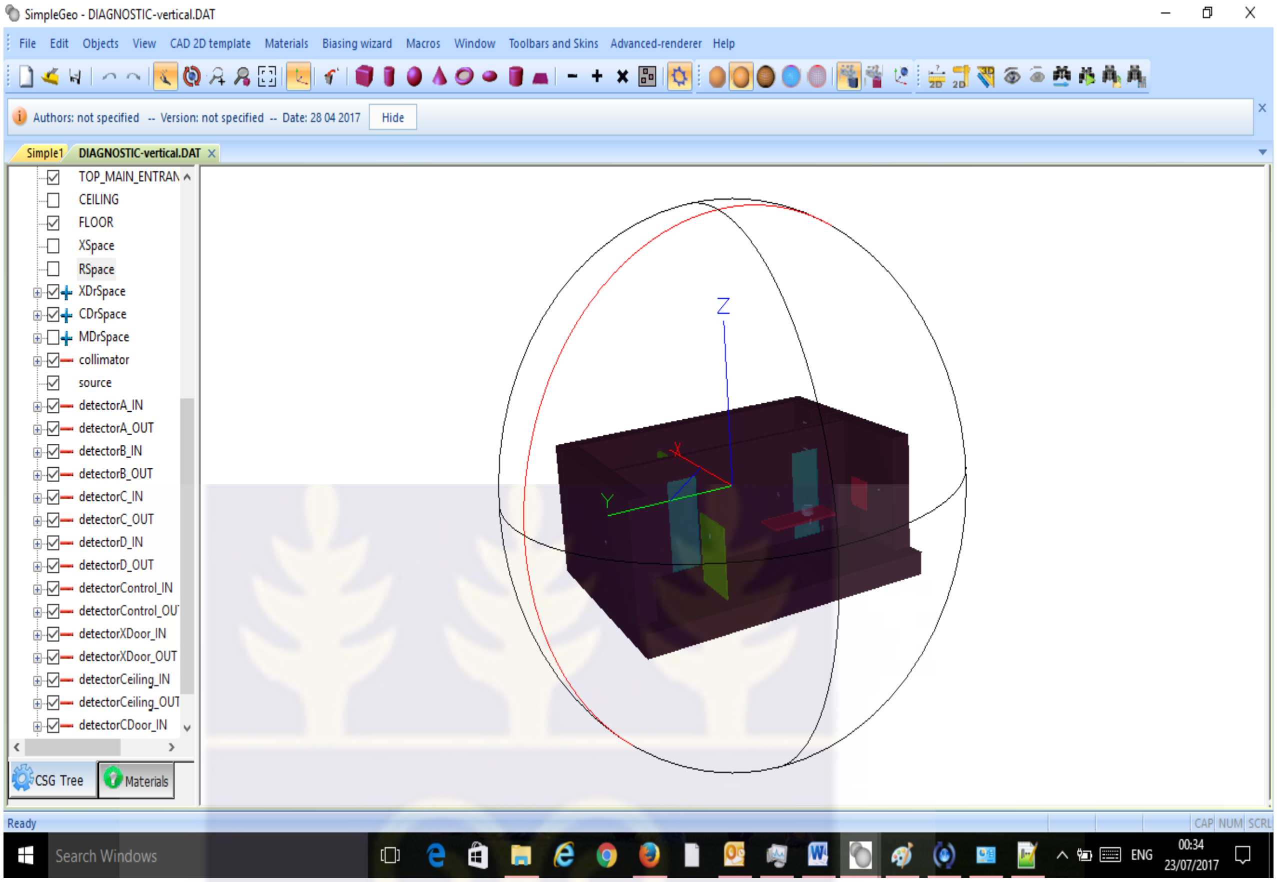
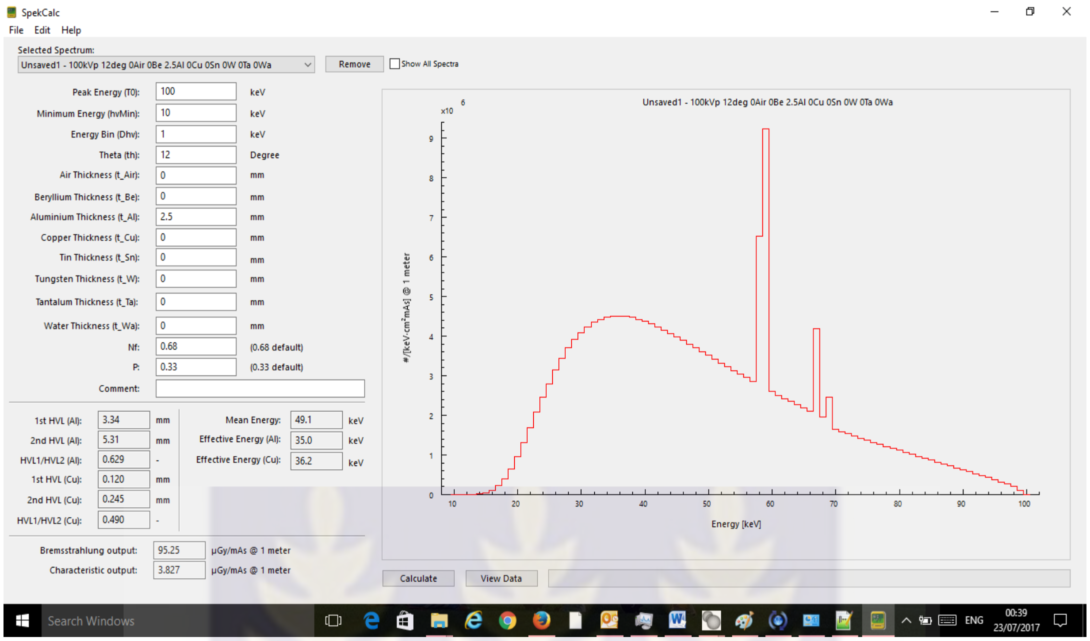


Fig 3 1: Interface of SimpleGeo during modelling process

3.9.2 X-ray Spectrum Generation

The x-ray photon energy spectrum was generated using SpekCalc. SpekCalc software provides the platform to generate any photon spectrum for studies. The specifications of 100 kVp, a tungsten anode angle of 12 degrees, and a 2.5 mm thick aluminium filter were chosen for SpekCalc to generate the necessary spectrum for diagnosis as shown in Figure 3.2. The detailed spectrum generated is shown in Figure 3.3. The mean energy of the spectrum was to 49.10 keV. There was a bremsstrahlung and characteristic x-ray output of 95.5 µGy/mAs and 3.83 µGy/mAs at 1 meter respectively.



Selected Spectrum: Unsaved1 - 100kVp 12deg 0Air 0Be 2.5Al 0Cu 0Sn 0W 0Ta 0Wa

Peak Energy (T0): 100 keV
Minimum Energy (hvMin): 10 keV
Energy Bin (Dhv): 1 keV
Theta (th): 12 Degree
Air Thickness (t_Air): 0 mm
Beryllium Thickness (t_Be): 0 mm
Aluminium Thickness (t_Al): 2.5 mm
Copper Thickness (t_Cu): 0 mm
Tin Thickness (t_Sn): 0 mm
Tungsten Thickness (t_W): 0 mm
Tantalum Thickness (t_Ta): 0 mm
Water Thickness (t_Wa): 0 mm
Nf: 0.68 (0.68 default)
P: 0.33 (0.33 default)
Comment:

1st HVL (Al): 3.34 mm
2nd HVL (Al): 5.31 mm
HVL1/HVL2 (Al): 0.629 -
1st HVL (Cu): 0.120 mm
2nd HVL (Cu): 0.245 mm
HVL1/HVL2 (Cu): 0.490 -

Mean Energy: 49.1 keV
Effective Energy (Al): 35.0 keV
Effective Energy (Cu): 36.2 keV

Bremsstrahlung output: 95.25 µGy/mAs @ 1 meter
Characteristic output: 3.827 µGy/mAs @ 1 meter

Fig 3 2: Interface of SpekCalc software generating the x-ray spectrum

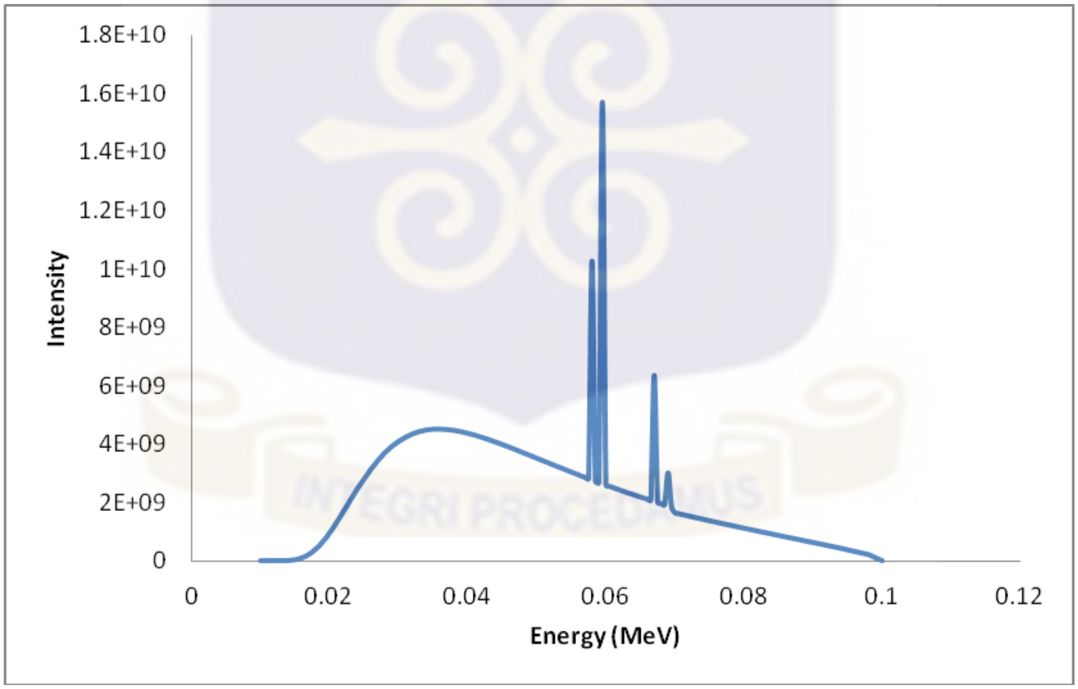


Fig 3 3: Photon energy spectrum for 100kVp

3.9.3 MCNP Simulation

The diagnostic x-ray verification model from SimpleGeo software is as shown in Figure 3.4 was converted into MCNP6 simulation input file. The verification model setup is as realistically done to effectively verify the modelled x-ray spectrum. The point source approach was employed to represent the x-ray tube. The verification simulation was conducted at100 kVp with a tally of relative error 5 % for accurate dosimeter results. The verification studies were conducted for all the x-ray machines considered for the study.

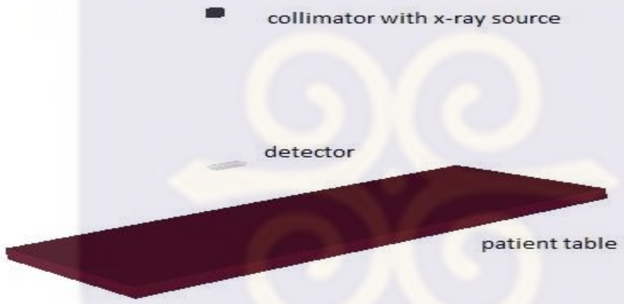
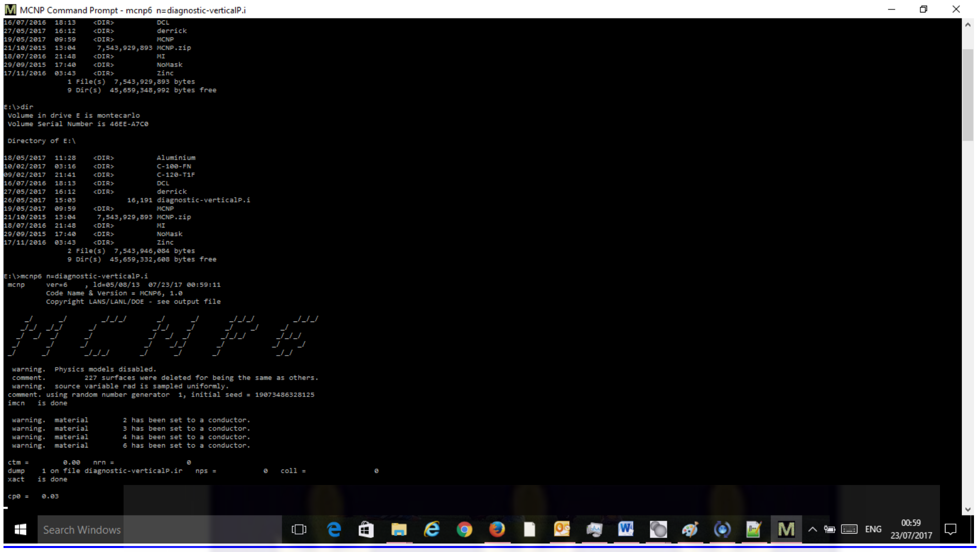


Fig 3 4: Diagnostic X-ray verification setup

The MCNP6 simulation input file for the investigative studies was generated from the SimpleGeo model shown in figure 3.5. The computational model was illustrated for vertical direction of the x-ray beam for abdomen, pelvis etc. examinations and horizontal direction of x-ray beam for chest examinations. The dosimetry points of interest are the dosimeter readings before and after all doors leading into x-ray room, the control room barrier, wall A, wall B, wall C and wall D as identified per facility.

Fig 3 5: 3D model of x-ray room

All the MCNP6 simulation input files were run on a Dell computer with specifications of Intel ® Core ™ i3-3227U CPU at 1.90GHz, installed memory of 4.00GB and a system type of 64 bit operating system as shown in Figure 3.6. The simulation tally of F6:p tally results (photon energy deposition per mass per particle) was used for the output of the simulations. One billion five hundred million (1.5×10^9) number of particles were tracked in order to have a good compromise between relative error and reasonable computational time. The photon energy deposited per unit mass in the dosimeters positioned at the regions of interest was tabulated and assessed using Microsoft excel.



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16/07/2016  18:13    <DIR>          DCL
27/05/2017  16:12    <DIR>          derrick
19/05/2017  09:59    <DIR>          MCNP
21/10/2015  13:04     7,543,929,893 MCNP.zip
18/07/2016  21:48    <DIR>          MI
29/09/2015  17:40    <DIR>          NoMask
17/11/2016  03:43    <DIR>          Zinc
               1 File(s)  7,543,929,893 bytes
               9 Dir(s)  45,659,348,992 bytes free

E:\>dir
 Volume in drive E is montecarlo
 Volume Serial Number is 46EE-A7C0

 Directory of E:\

18/05/2017  11:28    <DIR>          Aluminium
10/02/2017  03:16    <DIR>          C-100-FN
09/02/2017  21:41    <DIR>          C-120-T1F
16/07/2016  18:13    <DIR>          DCL
27/05/2017  16:12    <DIR>          derrick
26/05/2017  15:03            16,191 diagnostic-verticalP.i
19/05/2017  09:59    <DIR>          MCNP
21/10/2015  13:04     7,543,929,893 MCNP.zip
18/07/2016  21:48    <DIR>          MI
29/09/2015  17:40    <DIR>          NoMask
17/11/2016  03:43    <DIR>          Zinc
               2 File(s)  7,543,946,084 bytes
               9 Dir(s)  45,659,332,608 bytes free

E:\>mcnp6 n=diagnostic-verticalP.i
 mcnp     ver=6    , ld=05/08/13  07/23/17 00:59:11
          Code Name & Version = MCNP6, 1.0
          Copyright LANS/LANL/DOE - see output file

     _/      _/        _/_/_/      _/      _/      _/_/_/        _/_/_/
    _/_/  _/_/      _/            _/_/    _/      _/    _/    _/
   _/  _/  _/      _/            _/  _/  _/      _/_/_/      _/_/_/
  _/      _/      _/            _/    _/_/      _/          _/    _/
 _/      _/        _/_/_/      _/      _/      _/            _/_/

  warning.  Physics models disabled.
  comment.         227 surfaces were deleted for being the same as others.
  warning.  source variable rad is sampled uniformly.
 comment. using random number generator  1, initial seed = 19073486328125
 imcn   is done

  warning.  material        2 has been set to a conductor.
  warning.  material        3 has been set to a conductor.
  warning.  material        4 has been set to a conductor.
  warning.  material        6 has been set to a conductor.

 ctm =        0.00   nrn =                 0
 dump    1 on file diagnostic-verticalP.ir   nps =           0   coll =                0
 xact   is done

 cp0 =   0.03
```

Fig 3 6: Interface of MCNP6 running an input file

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses results for facilities FTN-CBD-01 and FTN04 based on the actual workload data obtained from the facilities. It presents values calculated for the normalized workload per patient, unshielded primary air kerma per patient at 1m, the kVp distribution of workload, and the scatter and leakage component. Comparison of results is made with NCRP 147 values. The calculated barrier thickness for the above mentioned facilities and dose rate readings are also presented.

The derived NCRP 147 values were used for the shielding barrier calculation requirement for facilities FTN-CBD-02, FTN-CBD-03 and FTN-05 as the actual workload data was not available. The corresponding dose rate readings are also presented.

3D images of the facilities developed from SimpleGeo tool kit and MCNP6 simulation results are also contained in this chapter.

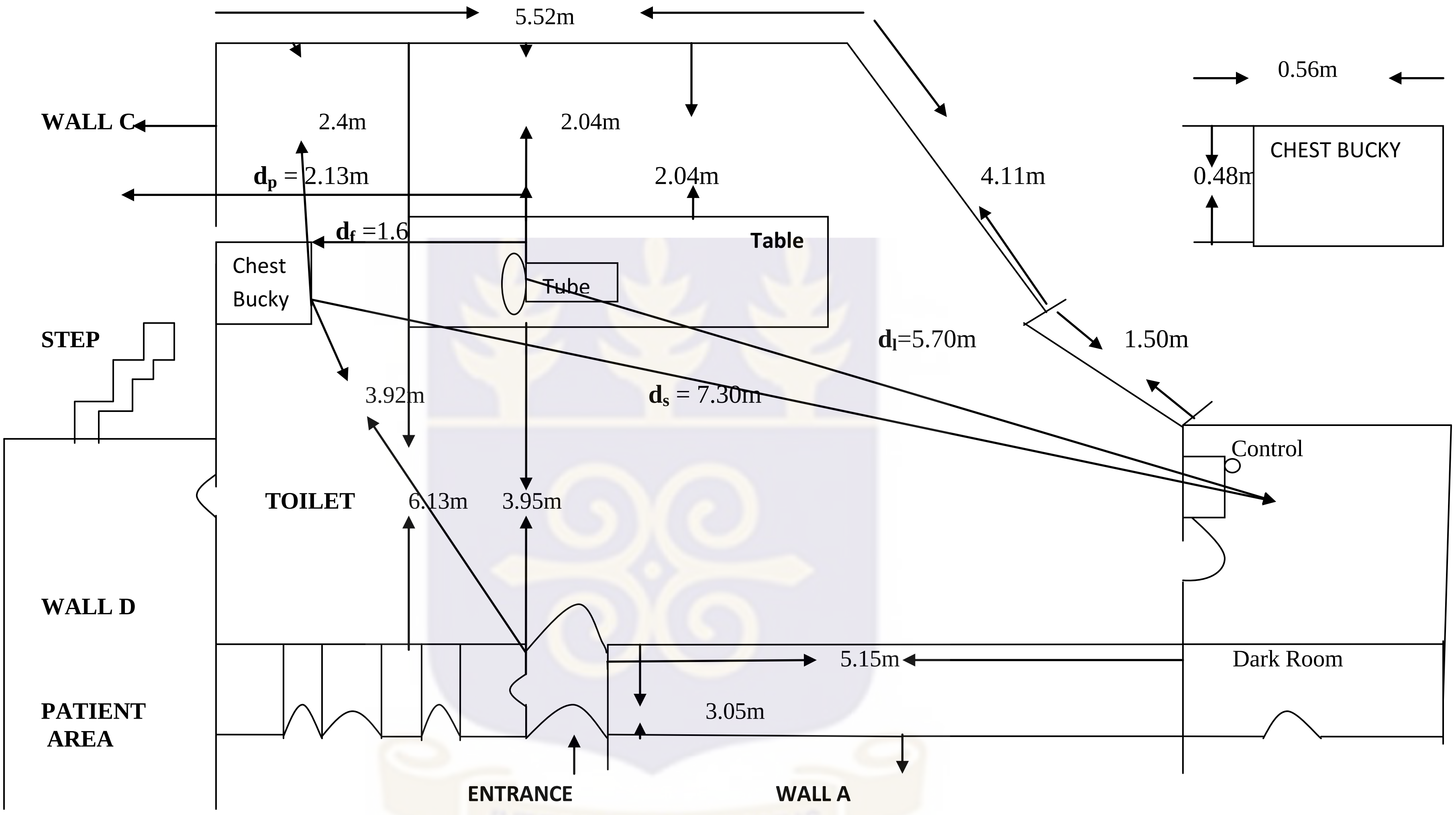


Fig 4.1.1 FACILITY: FTN-CBD-01

The areas that will be exposed to primary radiation include area behind Wall C on which there is the chest bucky and the floor for over table exposures. The floor will not be considered for primary shielding requirement since there is no occupied area beneath the floor. All other areas will only be exposed to secondary radiation. The facility operates with an average of 22 patients per day for 6 working days in the week. This gives a total of N = 132 Patients week^{-1} and an estimated 155 examination performed in a week in the radiography room. It was estimated that out of the 132 patients and 155 examinations, 96 chest bucky examinations (87 patients) and 59 over table exposures examinations (45 patients) are performed weekly.

4.1 Primary Radiation Component

Table 4 1: Workload distribution for facility: FTN-CBD-01

KVp	W(kVp)
50	0.00
55	0.00
60	0.00
65	0.00
70	0.06
75	0.31
80	0.12
85	0.15
90	0.15
95	0.00
100	0.00

Table 4.1 shows the kVp workload distribution for the facility.

Table 4 2: Normalized Workload per patient for facility: FTN-CBD-01

Room Type	Total Workload per Patient (W_{norm}) (mAmin patient^{-1})
Rad Room (chest bucky)	0.7
Rad Room (floor)	0.8
Rad Room (floor and other barriers)	1.5

Table 4.2 presents the normalized workload per patient

Table 4 3: Unshielded primary air kerma per patient at 1m for facility Rad Room (chest bucky): FTN-CBD-01

kVp	Workload kVp	K^1_w (kVp)	K_p^1 (kVp)
50	0.00	1.07	0.00
55	0.00	1.30	0.00
60	0.00	1.56	0.00
65	0.00	1.86	0.00
70	0.06	2.19	0.13
75	0.31	2.55	0.79
80	0.12	2.94	0.35
85	0.15	3.35	0.50
90	0.15	3.78	0.57
95	0.00	4.23	0.00
100	0.00	4.69	0.00
Unshielded primary air-kerma per patient at 1 m (K_p^1 mGy Patient^{-1})			**2.34**

Table 4.3 shows the unshielded primary air kerma per patient at 1m for the Rad Room (chest bucky)

Table 4 4: Unshielded primary air kerma for facility Rad Room (floor): FTN-CBD-01

kVp	Workload kVp	K^1_w (kVp)	K_p^1 (kVp))
50	0.00	1.07	0.00
55	0.03	1.30	0.04
60	0.00	1.56	0.00
65	0.00	1.86	0.00
70	0.04	2.19	0.08
75	0.29	2.55	0.74
80	0.09	2.94	0.25
85	0.23	3.35	0.77
90	0.08	3.78	0.32
95	0.07	4.23	0.30
100	0.00	4.69	0.00
	Unshielded primary air-kerma per patient at 1 m (K_p^1 mGy Patient^{-1})		**2.51**

Table 4 5: Comparison of calculated facility values with NCRP.147

Workload Distribution	Facility (W_{norm}) (mAmin patient^{-1})	NCRP W_{norm} (mA min patient^{-1})	Facility (K_p^1 mGy Patient^{-1})	NCRP (K_p^1 mGy Patient^{-1})
Rad Room (chest bucky)	0.7	0.6	2.3	2.3
Rad Room (floor and other barriers)	1.5	1.9	4.8	5.2

Table 4.5 presents a comparison of the values calculated for the facility based on the workload data with the standard NCRP 147 values.

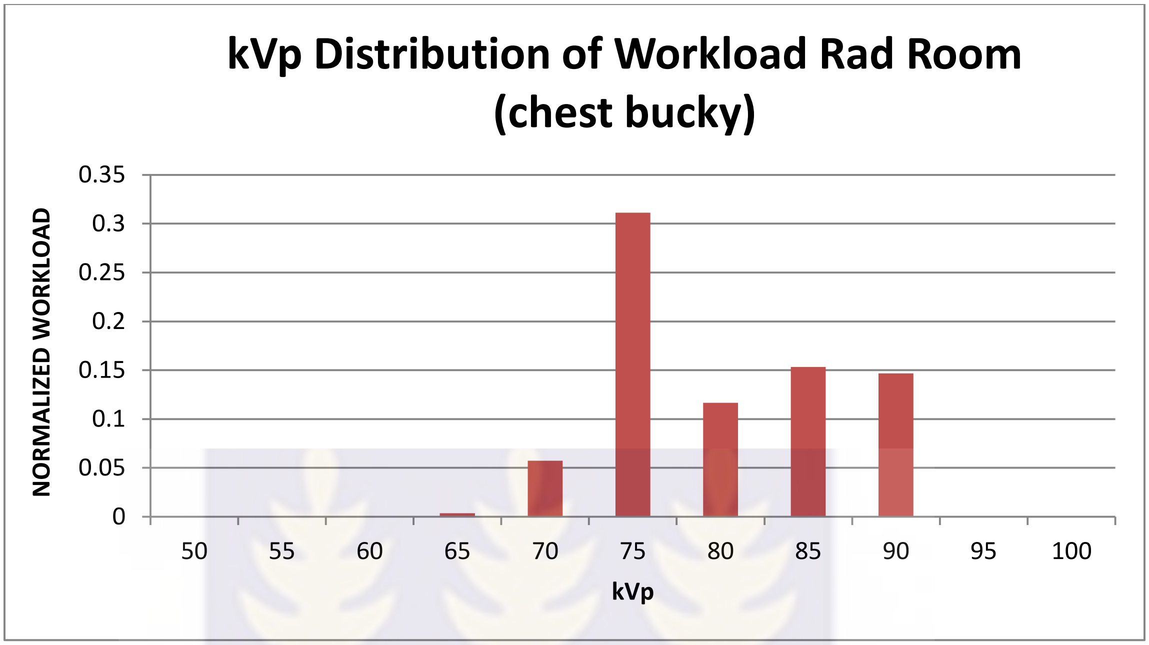


Fig 4.1 Workload Distribution Rad Room (chest bucky) FTN-CBD-01

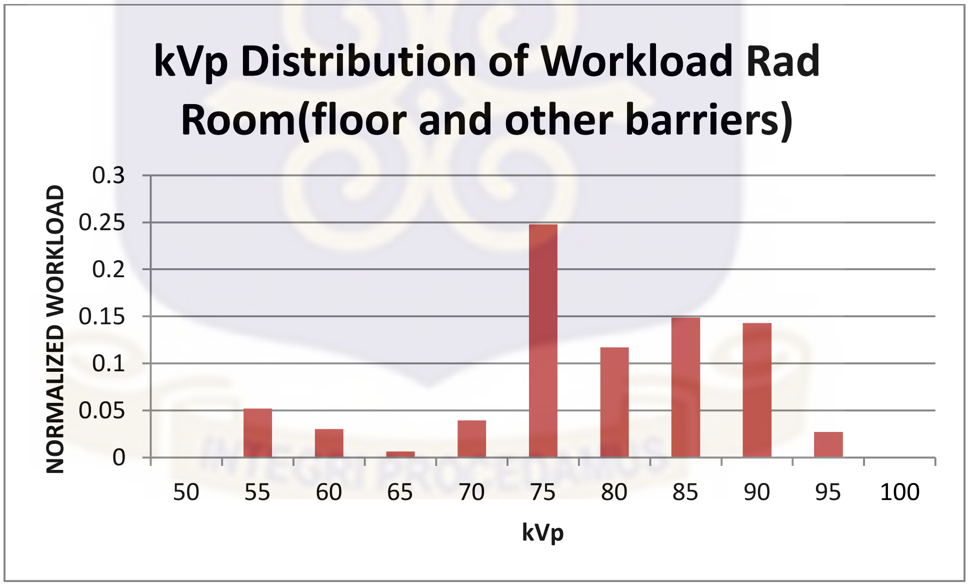


Fig 4.2 Workload Distribution Rad Room (floor and other barriers) FTN-CBD-01

Table 4 6: Calculated Use Factor for facility: FTN-CBD-01

Barrier	Facility (W_{norm}) (mAmin patient^{-1})	Use Factor
Rad Room (chest bucky)	0.7	0.5
Rad Room (floor)	0.8	0.5

Table 4.6 shows the calculated use factor for the facility.

4.2 Secondary Radiation Component

Table 4 7: Side scatter radiation calculated for 90 degree scatter Rad Room (chest bucky) FTN-CBD-01

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)
50	0.00	1.07	0.00	3.93	0.000
55	0.00	1.30	0.00	4.01	0.000
60	0.00	1.56	0.00	4.09	0.000
65	0.00	1.86	0.00	4.17	0.000
70	0.06	2.19	0.13	4.25	0.000
75	0.31	2.55	0.79	4.33	0.002
80	0.12	2.94	0.35	4.41	0.001
85	0.15	3.35	0.50	4.49	0.001
90	0.15	3.78	0.57	4.57	0.001
95	0.00	4.23	0.00	4.65	0.000
100	0.00	4.69	0.00	4.73	0.000
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0052**

Table 4.7 indicates the side scatter radiation calculated for 90 degree scatter for Rad Room (chest bucky)

Table 4 8: Side scatter radiation calculated for 90 degree scatter. Rad Room (floor) FTN-CBD-01

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)
50	0.00	1.07	0.00	3.93	0.0001
55	0.03	1.30	0.04	4.01	0.0000
60	0.00	1.56	0.00	4.09	0.0000
65	0.00	1.86	0.00	4.17	0.0002
70	0.04	2.19	0.08	4.25	0.0016
75	0.29	2.55	0.74	4.33	0.0006
80	0.09	2.94	0.25	4.41	0.0017
85	0.23	3.35	0.77	4.49	0.0007
90	0.08	3.78	0.32	4.57	0.0007
95	0.07	4.23	0.30	4.65	0.0000
100	0.00	4.69	0.00	4.73	0.0000
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0056**

Table 4.8 indicates the side scatter radiation calculated for 90 degree scatter for Rad Room (floor)

The unshielded leakage air kerma was calculated from equation 2.29 with the assumption that the intensity of leakage radiation with no housing is equal to that of the primary beam at 150kVp and 5mA at 1m

It is also assumed that at the given kVp, a lead lined housing of *x*=2.32mm is required to reduce the leakage radiation exposure rate at 1m to 100mR^{-1} (0.876mGy h^{-1}; 1.46 × 10^{-2})

Table 4 9 Unshielded air kerma Rad Room (chest bucky): FTN-CBD-01

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.07	0.00	3.93	0.000	0.0000
55	0.00	1.30	0.00	4.01	0.000	0.0000
60	0.00	1.56	0.00	4.09	0.000	0.0000
65	0.00	1.86	0.00	4.17	0.000	0.0000
70	0.06	2.19	0.13	4.25	0.000	0.0003
75	0.31	2.55	0.79	4.33	0.002	0.0020
80	0.12	2.94	0.35	4.41	0.001	0.0009
85	0.15	3.35	0.50	4.49	0.001	0.0013
90	0.15	3.78	0.57	4.57	0.001	0.0014
95	0.00	4.23	0.00	4.65	0.000	0.0000
100	0.00	4.69	0.00	4.73	0.000	0.0000
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0052**	
Leakage air kerma K_L (kVp)						**0.0059**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.0111**

Table 4.9 presents the unshielded air kerma Rad Room (chest bucky):

Table 4 10: Unshielded air kerma Rad Room (floor): FTN-CBD-01

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.07	0.00	3.93	0.0001	0.0001
55	0.03	1.30	0.04	4.01	0.0000	0.0000
60	0.00	1.56	0.00	4.09	0.0000	0.0000
65	0.00	1.86	0.00	4.17	0.0002	0.0002
70	0.04	2.19	0.08	4.25	0.0016	0.0020
75	0.29	2.55	0.74	4.33	0.0006	0.0007
80	0.09	2.94	0.25	4.41	0.0017	0.0021
85	0.23	3.35	0.77	4.49	0.0007	0.0009
90	0.08	3.78	0.32	4.57	0.0007	0.0008
95	0.07	4.23	0.30	4.65	0.0000	0.0000
100	0.00	4.69	0.00	4.73	0.0000	0.0000
50	0.00	1.07	0.00	3.93	0.0001	0.0001
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0056**	
Leakage air kerma K_L (kVp)						**0.0068**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.0124**

Table 4.10 shows unshielded air kerma Rad Room (floor)

Table 4 9: Unshielded air kerma Rad Room (all barriers) : FTN-CBD-0

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.07	0.00	3.93	0.0000	0.021
55	0.05	1.30	0.07	4.01	0.0001	0.021
60	0.03	1.56	0.05	4.09	0.0001	0.021
65	0.00	1.86	0.01	4.17	0.0000	0.022
70	0.04	2.19	0.09	4.25	0.0002	0.022
75	0.25	2.55	0.63	4.33	0.0014	0.023
80	0.12	2.94	0.34	4.41	0.0008	0.023
85	0.15	3.35	0.50	4.49	0.0011	0.024
90	0.14	3.78	0.54	4.57	0.0012	0.024
95	0.03	4.23	0.11	4.65	0.0003	0.024
100	0.03	4.69	0.00	4.73	0.0000	0.025
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0052**	
Leakage air kerma K_L (kVp)						**0.250**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.255**

Table 4 10: Comparison of side scatter for facility with NCRP147

Workload Distribution	Facility (side Scatter)	NCRP147 (Side Scatter)	Facility (K^1_{Sec})	NCRP147 (K^1_{Sec})
Rad Room (Chest Bucky)	5.2×10^{-3}	4.9×10^{-3}	1.1×10^{-2}	5.3×10^{-3}
Rad Room (floor or other barriers)	1.08×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-2}

Table 4.12 presents a Comparison of side scatter calculated for facility with NCRP147

4.3 Barrier Calculation Results

Table 4 11: Barrier shielding requirement: FTN-CBD-01

Barrier	**Existing Barrier Thickness (mm)** **Concrete /Wood**	**Calculated Thickness (mm)** **Concrete , Wood**	**Optional material Thickness (mm)**
	Primary Barrier		
Wall Containing the chest Image Receptor	450mm Concrete	58mm Concrete	
	Secondary Barrier		
Ceiling –Lecture Hall	450mm Concrete	52mm Concrete	
Control Room	450mm Concrete	15mm Concrete	0.1mm Lead for viewing window
Entrance Door	45mm Wood	10mm Wood	0.1mm Lead

Table 4.13 shows the thickness of barrier shielding calculated for the facility.

4.3 Radiation Dose Rate Measurement

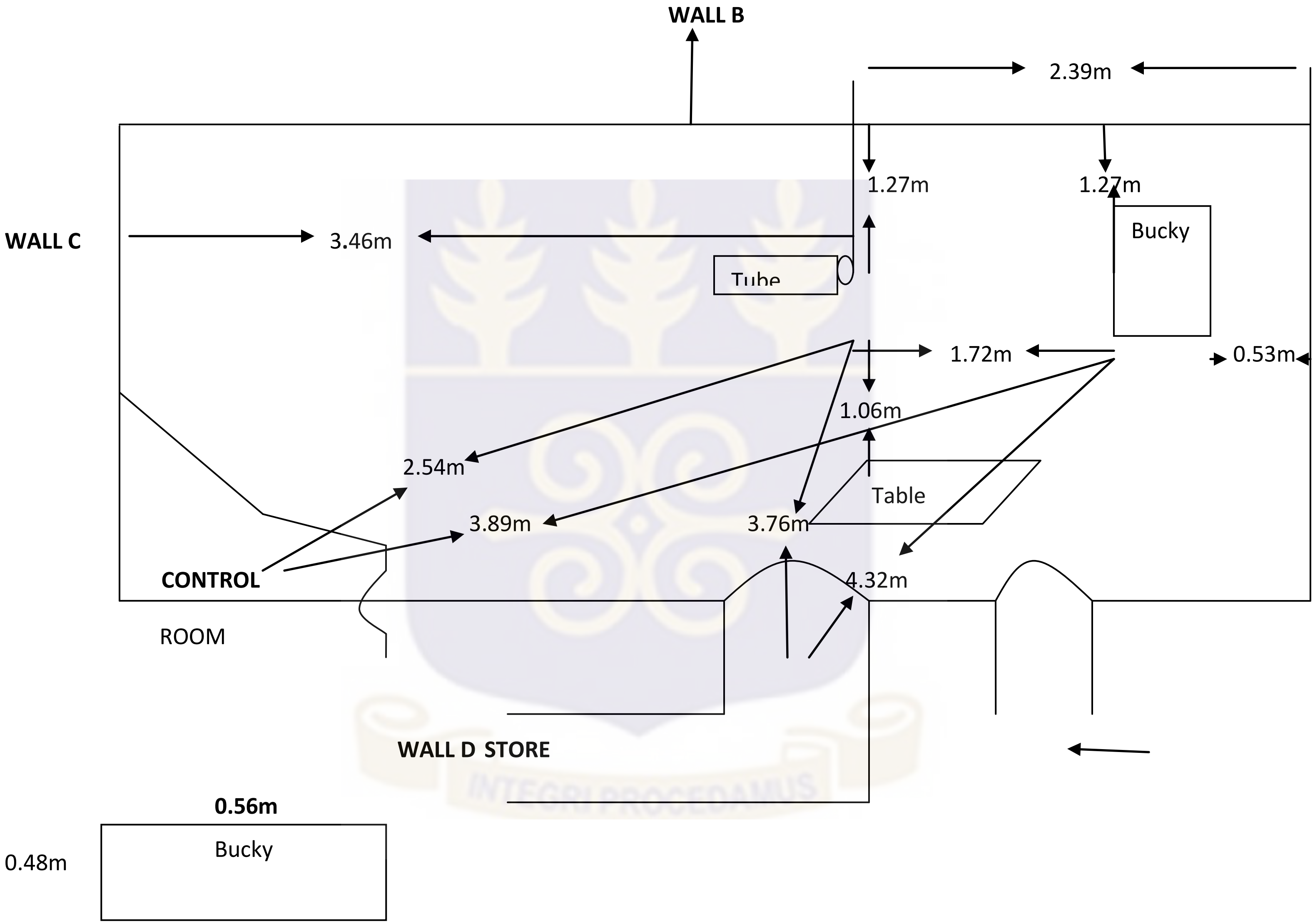
Table 4 12: Radiation Dose Rate measurement: FTN-CBD-01

Background (µSv/hr)	**0.04**	**0.03**	**0.03**

Dose Rate Reading (µSv/hr)		
Entrance to Radiographic Room	0.08	0.12
	0.07	0.06
Dose Rate reading behind the shielded cubicle (µSv/hr)		
	0.07	0.10
	0.10	0.07
	0.11	0.05
Wall C (µSv/hr)		
	0.05	0.08
Wall B (µSv/hr)		
	0.04	0.07
	0.08	0.06

Table 4.14 measured radiation dose rate for the facility

FTN-04


WALL B
2.39m
1.27m
1.27m
WALL C
3.46m
Bucky
Tube
1.72m
0.53m
1.06m
2.54m
Table
3.89m
3.76m
4.32m
CONTROL
ROOM
WALL D STORE
0.56m
0.48m
Bucky

The areas that will be exposed to primary radiation include area behind Wall C on which there is the chest bucky and the floor for over table exposures. The floor will not be considered for primary shielding requirement since there is no occupied area beneath the floor. All other areas will only be exposed to secondary radiation. The facility operates with an average of 18 patients per day for 5 working days in the week. This gives a total of N = 90 Patients week^{-1} and an estimated 102 examination performed in a week in the radiography room. It is estimated that out of the 90 patients and 102 examinations, 66 chest bucky examinations (59 patients) and 36 over table exposures examinations (31 patients) are performed weekly.

4.4 Primary Radiation Component

Table 4 13: Workload distribution for facility:FTN-04

kVp	W(kVp)
50	0.00
55	0.05
60	0.21
65	0.33
70	0.12
75	0.08
80	0.03
85	0.09
90	0.11
95	0.04
100	0.00

Table 4 14: Normalized workload per patient for facility FTN-04

Room Type	Total Workload per Patient (W_{norm}) (mAmin patient^{-1})
Rad Room (chest bucky)	0.5
Rad Room (floor)	0.6
Rad Room (floor and other barriers)	1.1

Table 4 15: Unshielded air kerma per patient for facility Rad Room (chest bucky) FTN-04

kVp	Workload kVp	$K^1{}_w$ (kVp)	$K_p{}^1$ (kVp)
50	0.00	1.22	0.00
55	0.03	1.22	0.13
60	0.01	1.22	0.20
65	0.16	1.21	0.28
70	0.09	1.22	0.20
75	0.05	1.22	0.15
80	0.02	1.22	0.11
85	0.03	1.22	0.12
90	0.10	1.22	0.21
95	0.00	1.22	0.00
100	0.00	1.22	0.00
	Unshielded primary air-kerma per patient at 1 m ($K_p{}^1$ mGy Patient^{-1})		**1.40**

Table 4 16: Unshielded air-kerma per patient for facility Rad Room (floor): FTN-04

kVp	Workload kVp	K^1_w (kVp)	K_p^1 (kVp))
50	0.00	1.22	0.00
55	0.02	1.22	0.09
60	0.12	1.22	0.21
65	0.17	1.21	0.27
70	0.03	1.22	0.09
75	0.03	1.22	0.10
80	0.02	1.22	0.08
85	0.07	1.22	0.15
90	0.02	1.22	0.08
95	0.04	1.22	0.11
100	0.00	1.22	0.00
Unshielded primary air-kerma per patient at 1 m (K_p^1 mGy Patient^{-1})			**1.18**

Table 4 17: Comparison of calculated facility values with NCRP.147

Workload Distribution	Facility (W_{norm}) (mAmin patient^{-1})	NCRP W_{norm} (mA min patient^{-1})	Facility (K_p^1 mGy Patient^{-1})	NCRP (K_p^1 mGy Patient^{-1})
Rad Room (chest bucky)	0.55	0.6	1.4	2.3
Rad Room (floor and other barriers)	1.08	1.9	2.6	5.2

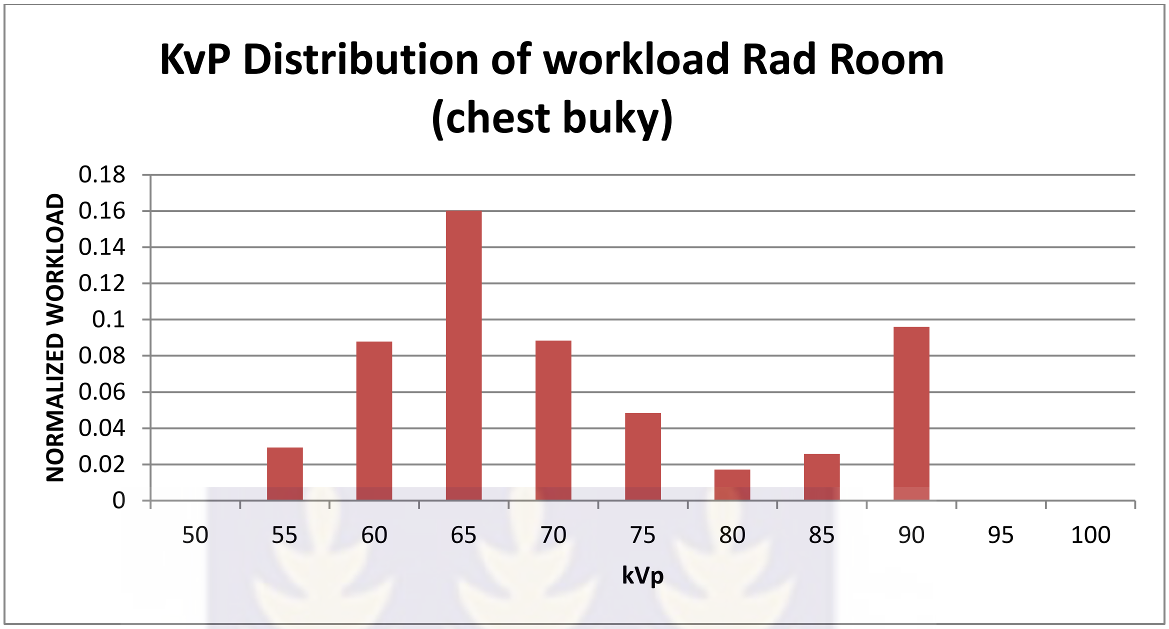


Fig 4.3 Workload Distribution Rad Room (chest bucky)

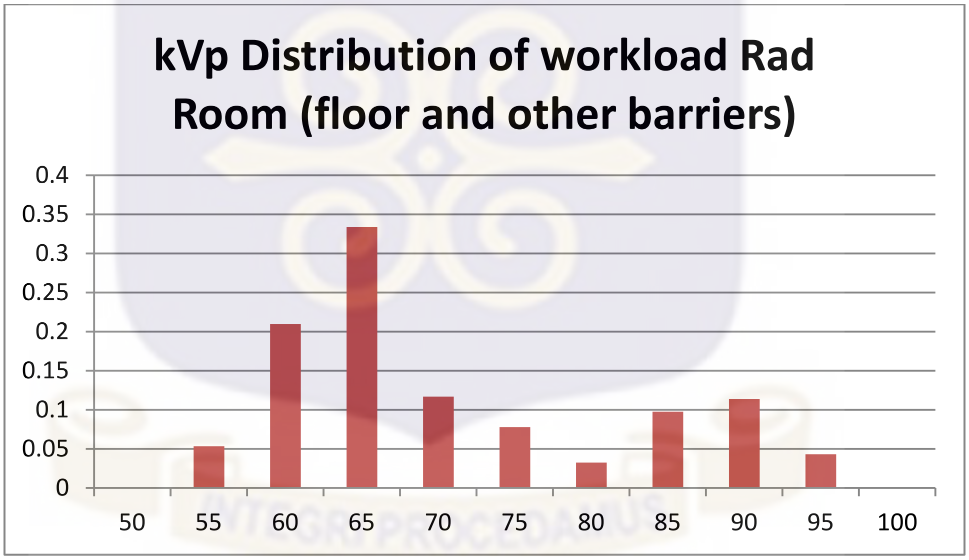


Fig 4.4 Workload Distribution Rad Room (floor and other barriers)

Table 4 18: Calculated use factor for facility FTN-04

Barrier	Facility (W_{norm}) (mAmin patient^{-1})	Use Factor
Rad Room (chest bucky)	0.55	0.51
Rad Room (floor)	0.53	0.49

4.5 Secondary Radiation Component

Table 4 19: Side scatter radiation calculated for 90 degree scatter Rad Room (chest bucky) FTN-04

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)
50	0.00	1.22	0.00	3.93	0.00
55	0.03	1.22	0.13	4.01	2.06E-04
60	0.01	1.22	0.20	4.09	3.30E-04
65	0.16	1.21	0.28	4.17	4.85E-04
70	0.09	1.22	0.20	4.25	3.44E-04
75	0.05	1.22	0.15	4.33	2.64E-04
80	0.02	1.22	0.11	4.41	2.00E-04
85	0.03	1.22	0.12	4.49	2.23E-04
90	0.10	1.22	0.21	4.57	3.87E-04
95	0.00	1.22	0.00	4.65	0.00
100	0.00	1.22	0.00	4.73	0.00
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0024**

Table 4 20: Side scatter radiation calculated for 90 degree scatter Rad Room (floor) FTN-04

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)
50	0.00	1.22	0.00	3.93	0.00
55	0.02	1.22	0.09	4.01	1.84E-04
60	0.12	1.22	0.21	4.09	4.38E-04
65	0.17	1.21	0.27	4.17	5.79E-04
70	0.03	1.22	0.09	4.25	2.07E-04
75	0.03	1.22	0.10	4.33	2.14E-04
80	0.02	1.22	0.08	4.41	1.78E-04
85	0.07	1.22	0.15	4.49	3.41E-04
90	0.02	1.22	0.08	4.57	1.93E-04
95	0.04	1.22	0.11	4.65	2.69E-04
100	0.00	1.22	0.00	4.73	0.00
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0026**

Table 4 21: Unshielded air kerma Rad Room (chest bucky) FTN-04

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.22	0.00	3.93	0.00	0.00
55	0.03	1.22	0.13	4.01	2.06E-04	5.29E-07
60	0.01	1.22	0.20	4.09	3.30E-04	8.45E-07
65	0.16	1.21	0.28	4.17	4.85E-04	1.24E-06
70	0.09	1.22	0.20	4.25	3.44E-04	8.81E-07
75	0.05	1.22	0.15	4.33	2.64E-04	6.77E-07
80	0.02	1.22	0.11	4.41	2.00E-04	5.13E-07
85	0.03	1.22	0.12	4.49	2.23E-04	5.72E-07
90	0.10	1.22	0.21	4.57	3.87E-04	9.91E-07
95	0.00	1.22	0.00	4.65	0.00	0.00
100	0.00	1.22	0.00	4.73	0.00	0.00
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0024**	
Leakage air kerma K_L (kVp)						**6.25E-06**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.0024**

Table 4 22: Unshielded air kerma at 1m Rad Room (floor) FTN-04

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.22	0.00	3.93	0.00	0.00
55	0.02	1.22	0.09	4.01	1.84E-04	4.91E-07
60	0.12	1.22	0.21	4.09	4.38E-04	1.16E-06
65	0.17	1.21	0.27	4.17	5.79E-04	1.54E-06
70	0.03	1.22	0.09	4.25	2.07E-04	5.53E-07
75	0.03	1.22	0.10	4.33	2.14E-04	5.71E-07
80	0.02	1.22	0.08	4.41	1.78E-04	4.76E-07
85	0.07	1.22	0.15	4.49	3.41E-04	9.10E-07
90	0.02	1.22	0.08	4.57	1.93E-04	5.15E-07
95	0.04	1.22	0.11	4.65	2.69E-04	7.17E-07
100	0.00	1.22	0.00	4.73	0.00	0.00
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)					**0.0026**	
Leakage air kerma K_L (kVp)						**6.95E-06**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.0026**

Table 4 23: Unshielded air kerma at 1m Rad Room (all barriers) FTN-04

kVp	W(kVp)	K^1_w	K^1_p (kVp)	a_1(90,kVp)	Ks(90,kvp)	Leakage air kerma K_L (kVp)
50	0.00	1.22	0.00	3.93	0.000	0.021
55	0.05	1.22	0.12	4.01	0.001	0.021
60	0.21	1.21	0.31	4.09	0.003	0.021
65	0.33	1.20	0.46	4.17	0.005	0.022
70	0.12	1.22	0.20	4.25	0.002	0.022
75	0.08	1.22	0.15	4.33	0.002	0.023
80	0.03	1.22	0.10	4.41	0.001	0.023
85	0.09	1.22	0.18	4.49	0.002	0.024
90	0.11	1.22	0.20	4.57	0.002	0.024
95	0.04	1.22	0.11	4.65	0.001	0.024
100	0.00	1.22	0.06	4.73	0.001	0.025
Unshielded Air Kerma (mGy patient^{-1}) at 1m (Side Scatter)”					**0.022**	
Leakage air kerma K_L (kVp)						**0.250**
Total secondary air kerma for both leakage and side scatter ,(K^1_{sec})						**0.272**

4.6 Barrier Calculation Results

Table 4 24: Barrier shielding requirement FTN-04

Barrier	**Existing Barrier Thickness (mm) Concrete /Wood**	**Calculated Thickness (mm) Concrete /Wood**	**Optional material Thickness (mm)**
Primary Barrier			
Wall Containing the chest Image Receptor	230mm Concrete	18mm Concrete	
Secondary Barrier			
Control Room	230mm Concrete 2.0mm Lead (viewing window)	15mm Concrete	0.1mm Lead for viewing window
Entrance Door	45mm Wood +0.1mm Lead		

4.7 Radiation Dose Rate Measurement

Table 4 25: Radiation dose rate measurement FTN-04

Background (µSv/hr) **0.03** **0.02** **0.04**

Dose Rate Reading (µSv/hr)		
Entrance to Radiographic Room	0.08	0.09
	0.08	0.07
Dose Rate reading behind the shielded cubicle (µSv/hr)		
	0.13	0.10
	0.08	0.05
	0.07	0.06
Wall C (µSv/hr)		
	0.07	0.07
	0.04	0.08
Wall B (µSv/hr)		
	0.07	0.08

FTN-CBD-02

FLOOR PLAN

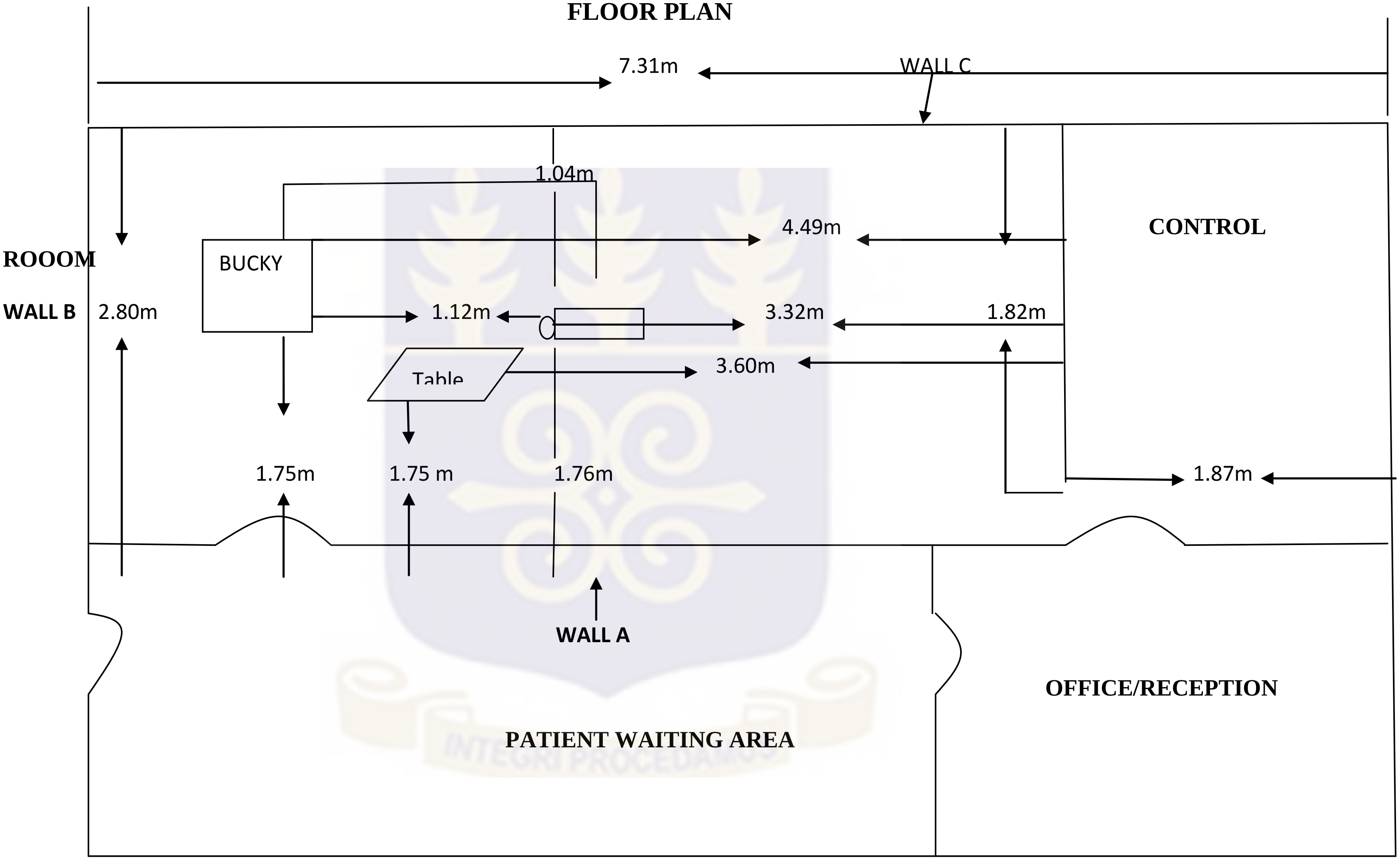


Table 4 26: Barrier shielding requirement: Facility FTN-CBD-02

Barrier	**Existing Material**	**Existing Thickness of Material (mm)**	**Calculated Thickness Required (mm)**	**Optional Material Thickness (mm)**
		Primary Barrier (Wall B)		
	Concrete	500mm	82mm concrete	Not Required
		Secondary Barrier		
Control Room	Viewing window-Glass Barrier : Wood	4mm Glass 40mm wood	0.04mm Lead 78mm Wood	15mm Plate Glass
Entrance Door	Steel Door	60mm	0.13mm Lead 1mm Steel	

Table 4 27: Radiation dose rate measurement FTN-CBD-02

Background	**0.04**	**0.03**
	Dose Rate Reading (μSv/hr)	
Entrance to Examination Room	0.06	0.07
	0.05	0.06
Waiting Room	0.03	0.04
	Dose Rate reading behind the shielded cubicle (μSv/hr)	
	0.10	0.07
	0.11	0.05
	Wall B (μSv/hr)	
	0.04	0.07
	Wall C (μSv/hr)	
	0.05	0.07

FTN-05

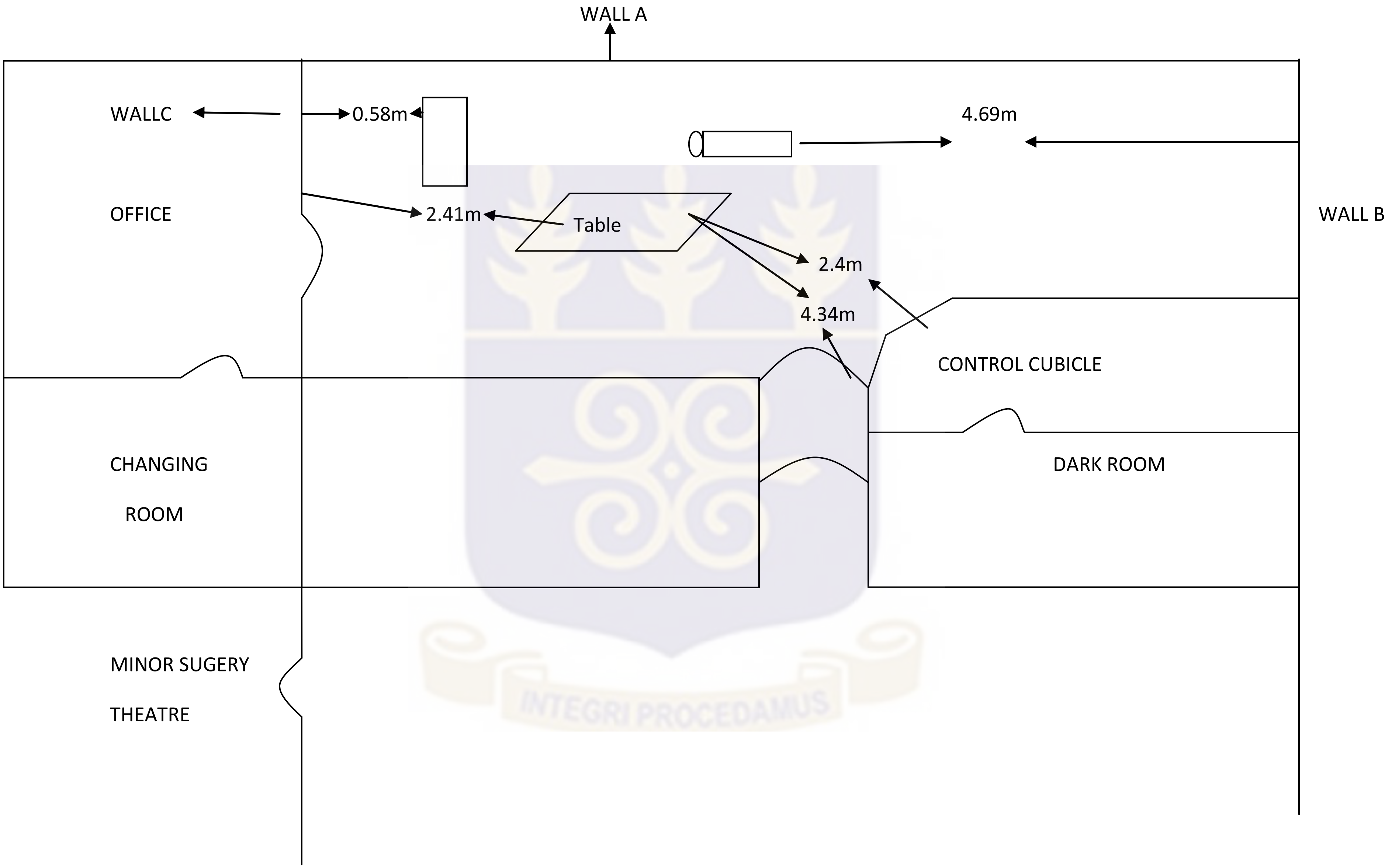

WALL A
WALLC
0.58m
4.69m
OFFICE
2.41m
Table
WALL B
2.4m
4.34m
CONTROL CUBICLE
CHANGING
ROOM
DARK ROOM
MINOR SUGERY
THEATRE

Table 4 28: Barrier shielding requirement FTN-05

Barrier	Existing Material	Existing Thickness of Material (mm)	Calculated Thickness Required (mm)	Optional Material Thickness (mm)
		Primary Barrier (Wall C)		
	Concrete	450mm	75.4mm concrete	
		Secondary Barrier		
Control Room	Viewing window- Glass Barrier : Wood	12mm glass 40mm Wood	0.1mm lead 50 mm wood	13mm Plate Glass
Entrance Door	Wooden Door	40mm	0.01mm Lead	0.1mm Steel

Table 4 29: Radiation dose rate measurement FTN-05

Background	**0.05**	**0.03**
Dose Rate Reading (μSv/hr)		
Entrance to Examination Room	0.11	0.08
	0.10	0.06
Dose Rate reading behind the shielded cubicle (μSv/hr)		
	0.14	0.08
	0.12	0.10
	0.09	0.07
Wall C (μSv/hr)		
	0.06	0.08
Wall B(μSv/hr)		
	0.06	0.07
Wall A (μSv/hr)		
	0.08	0.08

FTN-CBD-03

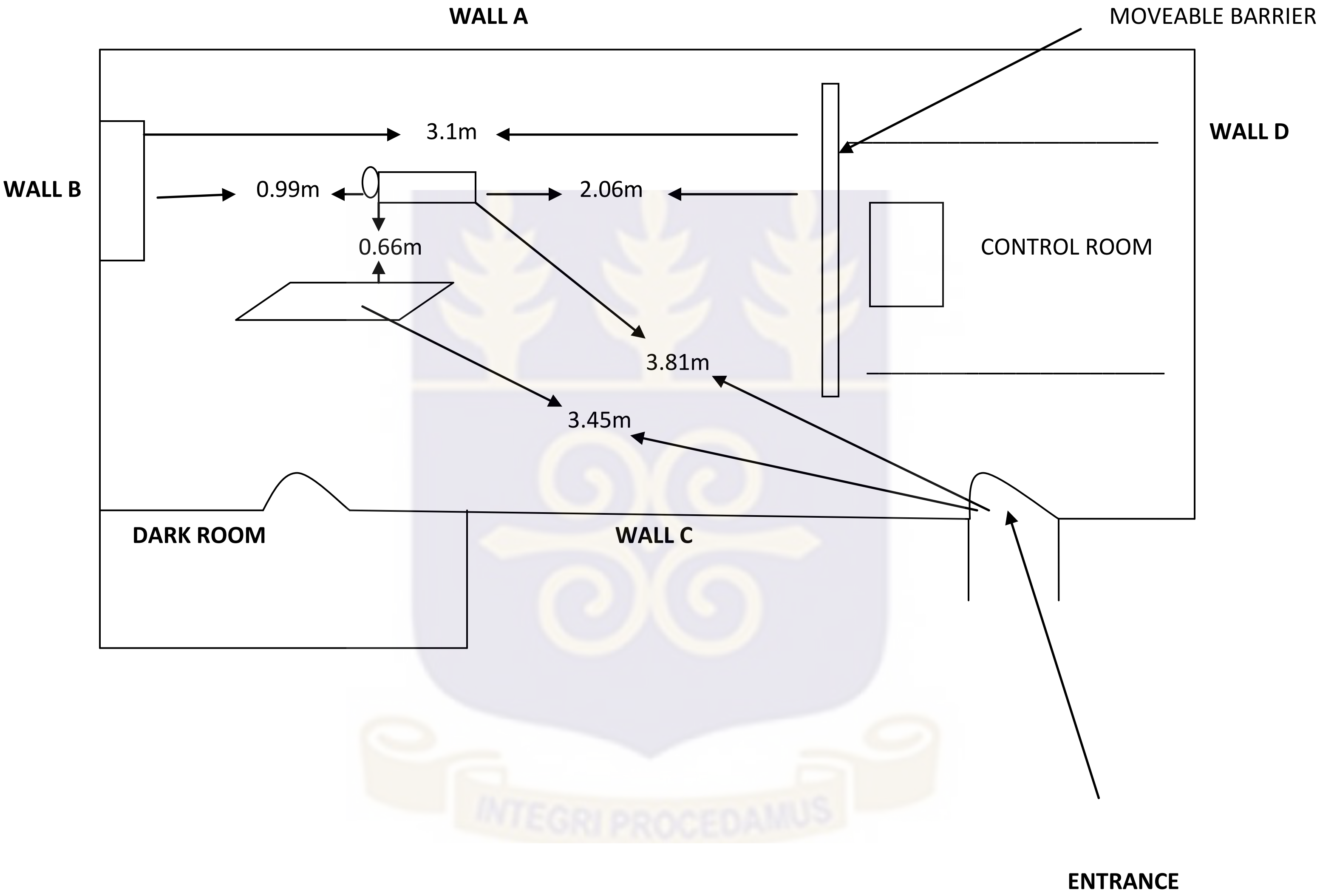

WALL A
MOVEABLE BARRIER
WALL B
WALL D
3.1m
0.99m
2.06m
0.66m
CONTROL ROOM
3.81m
3.45m
DARK ROOM
WALL C
ENTRANCE

Table 4 30: Barrier shielding requirement FTN-CBD-03

Barrier	Existing Material	Existing Thickness of Material (mm)	Calculated Thickness Required (mm)	Optional Material Thickness (mm)
Primary Barrier (Wall C)				
	Concrete	200mm	96mm concrete	
Secondary Barrier				
Control Room	Viewing window-Glass Barrier : Wood	12mm glass 40mm Wood	0.1mm lead 50mm wood	20mm Plate Glass
Entrance Door	Wooden Door	40mm	0.15mm Lead	1mm Steel

Table 4. 31: Radiation dose rate measurement FTN-CBD-03

Dose Rate Reading (μSv/hr)		
Entrance to Examination Room	0.11	0.10
	0.11	0.09
Dose Rate reading behind the shielded cubicle	(μSv/hr)	
	0.11	0.09
	0.08	0.08
Wall B (μSv/hr)		
	0.06	0.07
	0.08	0.08

Protective Barrier	Dose before Barrier (mGy)	Dose after Barrier (mGy)	Dose per day for 20 exposures (mGy)	ICRP dose (mGy) requirements per day	Additional shielding required (Yes/No)
Primary Barrier					
Wall A	8.80E-05	0.00E+00	0.00E+00	less than 0.00274	No
Secondary Barrier					
Control door	7.73E-05	2.32E-05	9.26E-04	less than 0.0548	No, dose less than 0.0548mGy per day
Entrance door	1.24E-04	3.89E-05	7.78E-04	less than 0.00274	No

Table 4. 32: Summary of Monte Carlo Simulations for radiation shielding at facility FTN-CBD-01

Protective Barrier	Dose before Barrier (mGy)	Dose after Barrier (mGy)	Dose per day for 20 exposures (mGy)	ICRP dose (mGy) requirements per day	Additional shielding required (Yes/No)
Primary Barrier					
Wall A	3.71E-04	0.00E+00	0.00E+00	less than 0.00274	No
Secondary Barrier					
Control door	3.26E-04	9.76E-05	3.90E-03	less than 0.0548	No, dose less than 0.0548mGy per day
Entrance door	5.23E-04	1.64E-04	3.28E-03	less than 0.00274	Yes

Table 4. 33: Summary of Monte Carlo Simulations for radiation shielding for facility FTN-04

Table 4 34: Summary of Monte Carlo Simulations for radiation shielding for facility FTN-CBD-02

Protective Barrier	Dose before Barrier (mGy)	Dose after Barrier (mGy)	Dose per day for 20 exposures (mGy)	ICRP dose (mGy) requirements per day	Additional shielding required (Yes/No)
Primary Barrier					
Wall A	3.02E-04	7.63E-06	1.53E-04	less than 0.00274	No
Secondary Barriers					
Control cubicle	6.90E-05	3.73E-06	7.46E-05	less than 0.0548	No, dose less than 0.0548mGy per day
Entrance door	3.13E-04	0.00E+00	0.00E+00	less than 0.00274	No

Table 4. 35: Summary of Monte Carlo Simulations for radiation shielding for facility FTN-05

Protective Barrier	Dose before Barrier (mGy)	Dose after Barrier (mGy)	Dose per day for 20 exposures (mGy)	ICRP dose (mGy) requirements per day	Additional shielding required (Yes/No)
Primary Barrier					
Wall A	3.32E-04	0.00E+00	0.00E+00	less than 0.00274	No
Secondary Barrier					
Control door	2.92E-04	8.74E-05	3.49E-03	less than 0.0548	No, dose less than 0.0548mGy per day
Entrance door	4.68E-04	1.47E-04	2.93E-03	less than 0.00274	Yes

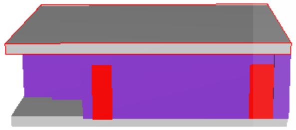
Table 4. 36: Summary of Monte Carlo Simulation for radiation shielding for facility FTN-CBD-03

Protective Barrier	**Dose before Barrier (mGy)**	**Dose after Barrier (mGy)**	**Dose per day for 20 exposures (mGy)**	**ICRP dose (mGy) requirements per day**	**Additional shielding required (Yes/No)**
Primary					
Wall A	2.38E-04	0.00E+00	0.00E+00	less than 0.00274	No
Secondary					
Control door	2.09E-04	6.26E-05	2.51E-03	less than 0.0548	No, dose less than 0.0548mGy per day
Entrance door	3.35E-04	1.05E-04	2.10E-03	less than 0.00274	Yes, since too close to required limit

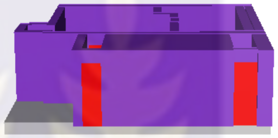
The summary of the simulation results presented in tables 4.34 – 4.38 shows the doses received behind the primary barrier made of concrete are below the ICRP dose requirement (mGy) per day and this can be mainly attributed to the adequacy of the existing wall thickness of each facility and as such no additional shielding will be required . However, it was observed that for facility FTN-BD-03, FTN-04 and FTN-05 additional shielding is required for the entrance door and control room barrier.

Fig 4 1 3D-Images of all facilities

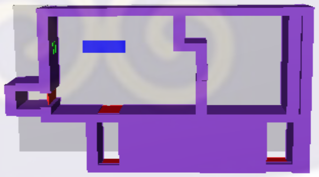
4.81 FTN-CBD-01- 3D IMAGE



Front View

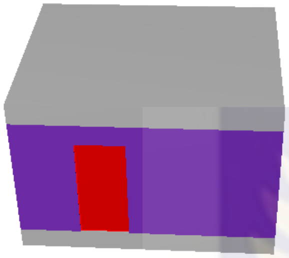


Side View

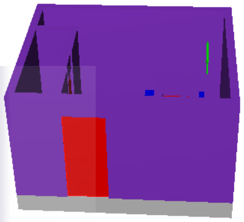


Top View

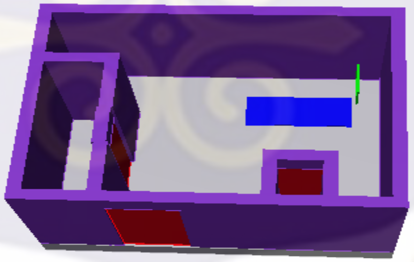
4.82 FTN-04- 3D IMAGE



Front View



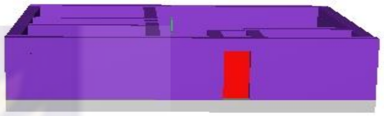
Side View



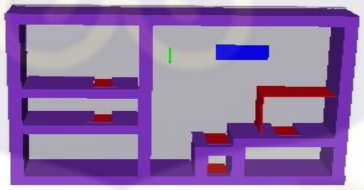
Top View

4.84 FTN-05- 3D IMAGE

Front View

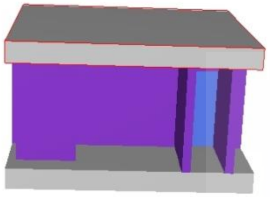


Side View

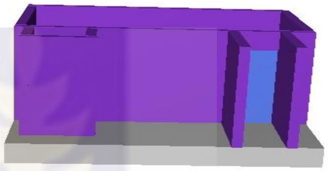


Top View

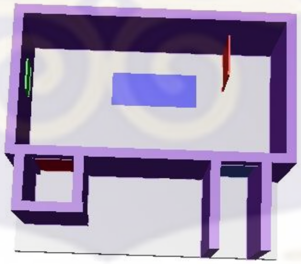
4.85 FTN-CBD-03 - 3D IMAGE



Front View

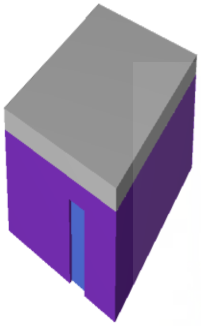


Side View

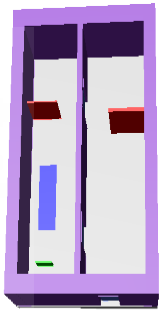


Top View

4.86 FTN-CBD-02 - 3D IMAGE



Front View



Side View

Top View

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Diagnostic radiology practice even though has contributed immensely to the diagnosis and treatment of patient may result in unnecessary exposure to patients, staff and the public if regulatory measures are inadequate. This study assessed the shielding integrity of selected x-ray imaging facilities in Freetown, Sierra Leone. From the mathematical calculations using the NCRP 147 approach, it was found that the existing wall thickness for each radiology facility was adequate. Secondary radiation shielding barrier requirement shows that facility FTN-CBD-03 and FTN-05 requires additional shielding for the entrance door, control room barrier and viewing window, for which the required thickness of the existing shielding material that will provide more attenuation was indicated. Alternative shielding materials were also recommended for all facilities where the study was carried out. MCNP6 simulation which was used for further verification of mathematical calculations also agrees with calculated values, and when compared with the ICRP dose requirement per day indicates doses are below the stipulated limit for most of the facilities except for facility FTN-CBD-03 and FTN-05. Although Radiation dose rate measurements around facilities are within acceptable limits, to be conservatively safe additional shielding would be required in the areas identified based on mathematical calculations and simulation results.

5.2 Recommendation

5.2.1 To Diagnostic X-ray Facilities

1. Efforts should be made to ensure that viewing window is fitted on the control room for facilities where there are no viewing windows.
2. Facilities with wooden entrance doors should ensure that the doors are fitted so as to eliminate gaps between doors and concrete barrier.
3. Radiographic rooms should not be used as a patient record room (as was observed in one facility) to ensure that staff doses are kept within acceptable limits.
4. Warning Lights should be fitted at the entrance door of the x-ray room.
5. Facilities that have acquired Thermoluminisent (TLD) badges must ensure that they are being worn properly and during working hours.
6. Access to the examination room for both patient and staff must be controlled.
7. Patient exposure records should be well documented.
8. Licensees should ensure that collimator lights that are not working (as was observed in one facility) are replaced so as to achieve highest level of protection for patient and staff.
9. Radiographers are mandated to use lead aprons always during exposure hours.
10. Licensees should ensure that Quality Control tests are done periodically.
11. Relatives or comforters are to be allowed in the examination room provided the patient will require such assistance. (as was observed in one facility)

12. Training and refresher training programs are to be organized for occupationally exposed staff.
13. Efforts must be made to address any non-compliance issued raised by regulatory authority inspectors.

5.2.3. To Regulatory Authority

1. The Regulatory Authority should ensure that TLD badges are exchanged regularly within the specified time frame.

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APPENDICES

Appendix 1 Workload Data Rad Room(Chest Bucky) FTN-CBD-01

Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs
1	1	80	40	30	1	74	32	59	1	74	40
2	1	76	40	31	1	70	40	60	1	74	40
3	1	78	3.2	32	2	70	32	61	1	68	32
4	1	72	25	33	1	74	4	62	1	80	50
5	1	74	40	34	1	70	32	63	1	70	25
6	1	72	32	35	1	72	32	64	1	66	25
7	1	66	20	36	1	80	50	65	1	70	32
8	1	80	100	37	1	86	64	66	1	70	32
9	1	74	40	38	1	70	32	67	1	68	25
10	1	70	32	39	1	72	32	68	1	68	25
11	1	66	25	40	1	76	40	69	1	70	32
12	1	76	50	41	1	64	20	70	1	70	25
13	1	68	32	42	1	78	50	71	1	70	25
14	1	76	40	43	1	76	40	72	1	74	40
15	1	70	32	44	2	80	80	73	1	74	40
16	1	66	40	45	1	78	50	74	1	72	32
17	1	76	40	46	1	74	50	75	1	74	40
18	1	72	32	47	1	80	20	76	1	74	40
19	1	74	40	48	1	70	32	77	1	74	40
20	1	80	50	49	1	70	32	78	1	80	50
21	1	70	32	50	1	76	50	79	2	84	64
22	1	74	32	51	1	70	32	80	1	74	40
23	1	70	32	52	1	70	32	81	1	70	25
24	1	70	32	53	2	84	80	82	1	70	25
25	1	68	32	54	2	74	80	83	2	76	64
26	3	84	25	55	1	74	40	84	1	72	32
27	1	76	80	56	2	78	80	85	1	74	32
28	1	72	100	57	1	66	25	86	1	68	25
29	1	72	50	58	1	74	40	87	1	68	25

Appendix 2 Workload Data Rad Room(floor) FTN-CBD-01

Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs
1	1	80	40	24	1	70	32
2	1	75	16	25	1	70	25
3	2	72	32	26	1	70	25
4	2	80	80	27	1	52	10
5	1	70	32	28	1	74	40
6	1	66	25	29	2	76	80
7	1	70	32	30	1	74	40
8	1	76	40	31	1	72	32
9	1	70	32	32	2	90	126
10	3	84	25	33	1	74	40
11	1	72	100	34	1	74	40
12	3	86	100	35	1	80	50
13	2	84	100	36	2	84	64
14	2	82	80	37	1	74	40
15	1	54	100	38	2	70	64
16	1	70	32	39	1	70	25
17	1	70	32	40	2	76	64
18	1	74	40	41	1	72	32
19	1	68	32	42	1	74	32
20	1	66	25	43	1	58	10
21	1	70	32	44	2	72	32
22	1	70	32	45	1	68	25
23	1	68	25				

Appendix 3. Workload Data Rad Room(Chest Bucky) FTN-04

Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs
1	1	54	16	21	1	55	8	41	1	70	32
2	1	55	18	22	2	60	32	42	1	71	32
3	1	54	28	23	1	50	16	43	1	75	30
4	1	60	32	24	1	50	16	44	1	83	38
5	1	64	28	25	1	50	8	45	1	85	38
6	2	60	30	26	1	52	16	46	1	76	38
7	1	64	30	27	1	66	32	47	1	70	32
8	1	65	32	28	1	68	32	48	2	70	32
9	1	65	32	29	1	65	30	49	1	80	32
10	1	64	30	30	1	58	28	50	1	80	32
11	1	68	32	31	2	62	28	51	1	50	18
12	1	68	32	32	1	62	30	52	1	60	30
13	1	58	30	33	1	50	18	53	1	64	30
14	2	58	30	34	1	64	28	54	1	68	32
15	1	56	28	35	1	60	30	55	1	52	22
16	1	60	32	36	1	55	25	56	1	55	25
17	1	55	30	37	1	52	16	57	1	60	30
18	1	56	30	38	1	65	32	58	1	64	30
19	1	55	22	39	2	65	32	59	1	71	32
20	2	56	22	40	1	60	30				

Appendix 4. Workload Data Rad Room (Floor) FTN-04

Patient	No of Procedures	kVp	mAs	Patient	No of Procedures	kVp	mAs
1	1	55	25	16	2	56	30
2	1	60	32	17	1	64	28
3	2	60	32	18	1	60	32
4	1	54	25	19	1	60	30
5	2	64	28	20	1	55	30
6	1	56	30	21	1	75	32
7	1	58	30	22	1	80	40
8	2	68	30	23	1	72	32
9	1	59	28	24	1	74	30
10	1	60	30	25	1	80	35
11	1	54	25	26	1	90	45
12	2	60	30	27	1	90	45
13	1	55	28	28	1	84	38
14	1	55	25	29	1	85	38
15	1	60	32	30	1	82	38