

**ASSESSMENT AND OPTIMIZATION OF OCCUPATIONAL RADIATION DOSES
IN FLUOROSCOPY GUIDED PROCEDURE AT KORLE - BU TEACHING
HOSPITAL, ACCRA, GHANA**

BY

RUTH NANA NJANTANG

(10633004)

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DECLARATION

“This thesis is a result of a research work undertaken by Ruth Nana Njantang in the department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. Mary Boadu and Mr. Prince Kwabena Gyekye.”

I hereby affirm that except for references which have been cited, this work is the product of my own research and it has not been presented in part or whole for any other degree in this University or elsewhere.

..... Date.....

Ruth Nana Njantang

Student

Certified by:

..... Date.....

Prof. Mary Boadu

Principal Supervisor)

..... Date.....

Mr Prince Kwabena Gyekye

Co-Supervisor

ABSTRACT

International Commission on Radiological Protection (ICRP) publication 85 of 2000 recommended the use of two dosimeters for the monitoring of staff performing fluoroscopically guided procedures. This study aimed to assess the dose to operators performing fluoroscopically guided procedures at Korle – Bu Teaching Hospital and evaluate possibility for dose reduction. Four Radiologists, the Interventional Radiologist and the assistant were monitored for a period of one month and four Cardiologists were monitored for two months. Two electronic dosimeters were used by each worker present in the room and the personal equivalent dose Hp (10) and Hp (0.07) were recorded after each procedure. The Kerma Area Product (KAP) and screening time were also recorded per procedure. The scattered radiation dose rate was measured using a water phantom at 1 m from the focal spot, 160 cm from the floor at 0°, 90°, 120° and 180° for 3 projection of the tube (RAO 30°, LAO 30° and AP 0°). The patient dose and screening time at Radiology Department (over couch tube) were [1.89 - 14.38] Gy.cm², (0.2 - 2.5) min; [3.76 - 44.16] Gy.cm², (0.3 - 3.1) min and [8.7 - 60.77] Gy.cm², (1.9 - 10.9) min for Retrograde Urethrogram (RUG), Hysterosalpingography (HSG) and special cases respectively. The patient dose and screening time range at Cardiology (under couch tube) were [14.24 - 120.61] Gy.cm², (1.7 - 16.3) min, [42 - 237] Gy.cm², (9.70 - 43) min and [4.37 - 33.56] Gy.cm², (4.30 - 11.8) min for Coronary Angiogram (CA), Percutaneous Coronary Intervention (PCI) and Right Heart Catheterization (RHC) respectively. The dose range per procedure to Cardiologists was [0.1 - 42.15] μSv, [1.2 - 31.2] μSv and [0.1 - 2.75] μSv for the CA, PCI and RHC respectively. The range of the estimated monthly effective dose, and eye lens dose to Cardiologists and Radiologists were [0.01 -

0.07] mSv, (0.15, 0.30) mSv and [0.03 – 0.12] mSv, (0.53 – 3.39) mSv respectively. The interventional procedures were found to be lengthier with exposure time of (52 – 76.4 min), and delivered relatively high dose (47.13 – 412.23 Gy.cm²) to patients. The Interventional Radiologist and the assistant received an effective dose of 0.09 mSv, 0.03 mSv respectively and eye lens dose of 1.2 mSv, 0.33 mSv respectively. A weak but significant relationship ($R^2 = 0.32$, $p\text{-value} < 0.05$) was found to exist between patient dose and staff effective dose, meaning that staff dose is influenced by other factors. Generally, the staff effective dose and eye lens dose to Cardiologists and Radiologists were below the acceptable limits (1.67 mSv/month) except for one Radiologist whose eye lens dose exceeded the limit by a factor of 2. Therefore, the use of a ceiling suspended screen is highly recommended in radiology to reduce the eye lens dose. Monte Carlo simulation of the distribution of radiation in the room highlighted the safest position that can be occupied by the staff as a dose reduction technique to reduce the dose. The implementation of the proposed radiation safety programme is encouraged for optimization of protection in both departments.



DEDICATION

This work is dedicated to the Strength of my life, My Heavenly Father, the Almighty
GOD.



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LIST OF ABBREVIATIONS

| | |
|--------|--|
| IAEA | International Atomic Energy Agency |
| ICRU | International Commission on Radiation Units and Measurements |
| PET | Positron Emission Tomography |
| QA | Quality Assurance |
| WHO | World Health Organization |
| NCRP | National Council on Radiation Protection |
| CONRAD | European Coordinated Network for Radiation Dosimetry |
| HSG | Hysterosalpingogram |
| IVU | Intravenous Urogram |
| MCUG | Mituring Urethrogram |
| RUG | Retrograde Urethrogram |
| CT | Computed Tomography |
| MRI | Magnetic Resonance Imaging |
| NCTC | National Cardiothoracic Center |
| QC | Quality Control |
| RTI | Radiation To Information |
| USB | Universal Serial Bus |
| RAMSRI | Radiological and Medical Science Institute |
| GAEC | Ghana Atomic Energy Commission |
| HVL | Half Value Layer |
| LCD | Liquid Crystal Display |

| | |
|-------|---|
| EPD | Electronic Personal Dosimeter |
| MCNP | Monte Carlo N - Particle |
| LED | Light Emitting Diode |
| OEW | Occupationally Exposed Worker |
| NM | Nuclear Medicine |
| TLD | Thermoluminescent Dosimeter |
| OSL | Optical Simulated Luminescence |
| ICRP | International Commission on Radiological Protection |
| ALARA | As Low As Reasonable Achievable |
| KBTH | Korle Bu Teaching Hospital |
| CCD | Charge – Coupled Device |
| Cs I | Cesium Iodine |
| BSS | Basic Safety Standard |
| Gy | Gray |
| mA | milli Ampere |
| kVp | kilo Voltage peak |
| KAP | Kerma Area Product |
| DAP | Dose Area Product |
| Sv | Sievert |
| BEIR | Biological Effect of Ionizing Radiation |
| DDREF | Dose and Dose Rate Effectiveness Factor |
| LSS | Life Span Study |

| | |
|---------|--|
| UNSCEAR | United Nation Scientific Committee of the Effect of Atomic Radiation |
| DD | Doubling Dose |
| IEC | International Electrotechnical Commission |
| APD | Active Personal Dosimeter |
| CA | Coronary Angiography |
| PCI | Percutaneous Coronary Intervention |
| RHC | Right Heart Catheterization |
| NRC | National Research Council |
| RSO | Radiation Safety Officer |
| LAO | Left Anterior Oblique |
| RAO | Right Anterior Oblique |
| AP | Anterior Posterior |
| LANL | Los Alamos National Laboratory |
| ISO | International Organization for Standardization |
| IRPA | International Radiation Protection Association |
| DNA | Deoxyribonucleic Acid |
| CathLab | Catheterization Laboratory |
| SSDL | Secondary Standard Dosimetry Laboratory |

| | |
|-----|--------------------------------|
| AHA | American Heart Association |
| ACC | American College of Cardiology |
| NRA | Nuclear Regulatory Authority |



CHAPTER ONE

1.0. Introduction

In the introductory part of this study, the background, the statement of the problem, justification, objectives and scope of the study are clearly defined.

1.1. Background to the study

Medical exposure from X-rays and nuclear medicine is the largest man-made source of radiation exposure, representing a mean effective dose of 1.0–3.0 mSv per head per year (Mettler *et al*, 2009). The worldwide population exposure from medical radiation has been shown to increase, and the use of procedures (both diagnostic and therapeutic) with a high radiation dose has been growing steadily (Kim *et al*, 2008; Vano *et al*, 2009; Vassileva *et al*, 2013). Radiation exposure is a significant concern for interventional cardiologists and patients due to the increasing workloads and the complexity of procedures over the last decade (ICRP, 2013).

With fluoroscopy the patient is imaged in real time to guide minimally invasive procedures that form part of the diagnostic and interventional procedures, and this requires medical and technical staff to directly participate in the procedures. Occupationally Exposed Workers (OEWs) in fluoroscopy procedures are likely to receive high exposure, especially for the unshielded parts of the body which are: the extremities and head (Vano *et al*, 2010; Vano *et al*, 2013). Rehani *et al* (2010) reported lens opacities detected among some Interventional Radiologists and Cardiologist. The primary operator who stays closer to the patient is the most exposed

to radiation among all staff present in the room during interventional procedures (Kong *et al*, 2015). Many studies have been done so far concerning occupational exposure in fluoroscopy guided procedures around the world, mostly in Europe and America (Sanchez, 2011; Sandblom *et al*, 2013; Kostas *et al*, 2016; Szumska *et al*, 2016). A study performed in Netherlands, has estimated median occupational effective dose at 3 μSv per procedure for the interventional radiologist, 0.4 μSv per procedure for the assistant radiologist and maximum occupational effective dose for technologists 0.4 mSv (Joemai, 2009).

Radiation safety in the practice of interventional cardiology has been addressed by several professional bodies. UNSCEAR in 2008 report states that fluoroscopic procedures represent the largest source of occupational exposure in medicine (UNSCEAR, 2008). In 2009, the American Heart Association (AHA) Science Advisory recommended the reference doses of common cardiology examinations (Gerber *et al*, 2009) and in 2010 the American College of Cardiology (ACC) committee also expressed the need for appropriate and optimal use of radiation techniques in cardiology (Brindis and Douglas, 2010).

The continuous and systematic use of adequate protective equipment such as protective apron, thyroid shield, lead gloves, protective glasses, ceiling-suspended glass screen and lead curtain can significantly reduce exposure to the workers directly involved in interventional procedures. However, study on detailed monitoring of OEWs in fluoroscopy guided procedure in many facilities is still lacking. Botwe *et al* (2015) in a study carried out at the biggest referral hospital in Ghana showed that the radiation

monitoring of staff was unsatisfactory and did not meet required standard and stated that workers were monitored by the means of TLD badges only.

1.2. Statement of the Problem

Among all medical staff, those performing fluoroscopically guided procedures (such as Cardiologists and interventional radiologists.) are likely to receive the highest exposure to ionizing radiation. The eye's lens, extremities and thyroid can receive high radiation doses (Ciraj-Bjelac *et al*, 2010; Vano *et al*, 2010; Ciraj-Bjelac *et al*, 2012; Vano *et al*, 2013). The eye lens exposure results in the prevalence of lens opacities and cataracts among Cardiologists, Radiologists. This indicates the relevance of optimization of radiological protection in fluoroscopically guided procedures (Sandblom *et al*, 2013). Unlike other activities involving ionizing radiation, for which the exposure of the staff is predictable (optimization can be performed in advance), optimization of radiation protection in interventional radiology is complex and has to be performed during the procedure under varying and sometimes difficult situation such as unstable patient who require individual care. The nature of the procedures, the high individual workload and the difficulties in radiation protection measures justify the need for detailed occupational dosimetry studies. Studies performed in Ghana on fluoroscopy examinations were focused on patient dosimetry (Gyekye *et al*. 2009; Gyasi *et al*. 2012). The survey of literature indicates that there is no empirical data available on dose estimation of individuals working in specific fluoroscopy guided procedures in Ghana. In National Cardiothoracic Center, according to the patient data available in book record, the number of procedures has grown from 15 procedures / year (2000 – 2010) to 25 – 30 procedures / year (2011 – 2015). With the installation of the new cathlab in October

2016 the number of procedures has increased up to (22 – 24) procedures monthly. This increasing number of procedures shows the importance of intensifying personal monitoring programme at the Center. In addition, the International Commission on Radiological Protection in the statement on tissue reactions on 21 April 2011 recommend for occupational exposure in planned exposure situations, the revised equivalent dose limits for the lens of the eye are 20 mSv in a year, averaged over 5 consecutive years (i.e. 100 mSv in 5 years), and 50 mSv in any single year. These limits replace the previous limit on equivalent dose of 150 mSv in a year and the threshold in absorbed dose is now considered to be 0.5 Gy (ICRP, 2011; IAEA, 2014).

1.3. Research Objective

This study aims to estimate dose to medical staff during fluoroscopically guided procedures and evaluate possibilities for dose reduction.

The specific objectives of the study include the following:

- Estimate eye lens and effective dose to medical staff during selected fluoroscopy guided procedures.
- Use Monte-Carlo simulation to investigate the radiation dose distribution in the room to evaluate the possibilities of dose reduction.
- Investigate the factors that influence staff doses such as workload, type of procedure, patient dose, etc.
- Assess detrimental risk to the workers and propose recommendations aimed at staff dose reduction for clinical routine.

1.4. Relevance and justification

The purpose of routine monitoring for occupational exposure is to verify and demonstrate compliance with the regulatory or international dose limits, provide information on dose levels for the optimization of protection, to keep the dose as low as reasonably achievable (ALARA) and identify working practices that minimize the doses. The findings of this study on occupational doses will serve as a baseline data for future dose optimization efforts in fluoroscopically guided procedures in Ghana and may trigger the effective implementation of a radiation protection programme. Additionally, this study is going to help understand the influence of staff doses by the type of procedure performed, the individual workload, the use of radiation protection tools and the methodology of dose measurement. Lastly, staff dose reduction techniques suggested from this study for clinical trials will aid in the optimization of staff protection.

1.5. Scope and Delimitation

This research covered staff performing fluoroscopically guided procedures whilst standing in the examination room in radiology and cardiology departments at the Korle-Bu Teaching Hospital (KBTH). For investigative studies, Monte Carlo N-Particle code was used to effectively experiment on possible staff dose reduction techniques. The radiation exposure to the staff's whole body, eye lens and the study of the scatter radiation in the room of examination will be the dosimetry scope.

This study is limited to the dosimetry of the staff and does not include patient protection.

The dosimetry of the staff is also only limited to the whole body and eye lens exposures

and does not include any other organs. Only fluoroscopically guided procedures in the radiology and cathlab of the KBTH were considered.



CHAPTER TWO

2.0. Literature Review

This chapter present the general physics behind fluoroscopy: basic science, optimal use, Patient and operator protection. The principle of dose measurements and risk associated with radiation is described.

2.1. Physics behind Fluoroscopy: X-ray Production and Interaction

X-ray was discovered in 1895 when Wilhem Conrad Roentgen noticed that a screen coated with a barium-compound glowed when it was subjected to what would later me named X-rays. It is a form of electromagnetic waves generating enough radiation to be ionizing. Other electromagnetic waves include visible light, radio waves and gamma rays (Davros, 2007).

2.1.1. X-ray production

X-rays are generated when the energy state of an electron change. This is achieved when a heated filament (cathode) produces electrons which are accelerated to a tungsten target (anode) by applying a high voltage (50 – 150 kVp) to the tube. The electron creates an electric field that interacts with other atomic particles of the anode material. This result in the release of energy in the form of X-ray as shown in figure 2.1.

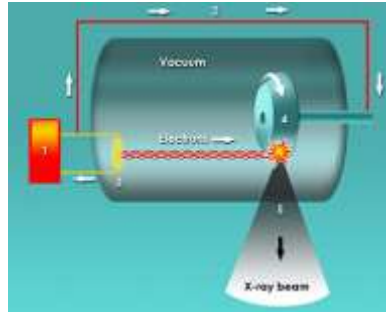


Figure 2.1: The X-ray tube (Source: www.radiologymasterclass.co.uk)

2.1.2. X-ray Interactions with Matter

When photons pass through a material, some interact with particles in the medium and their energy can be totally absorbed or scattered. Other photons travel completely through the medium without any interaction resulting in an image. This is called “complete penetration”. In diagnostic radiology, the two most important interactions of X-ray with tissue are: the photoelectric effect and Compton Effect. Depending on the type of interaction of electron with the target material, continuum and characteristic x-rays are produced.

2.1.2.1. Total absorption or photoelectric effect

This occurs when a low energy (low kVp) photon transfers the totality of its energy to the inner shell electron of the atom. This electron is ejected from the atom leaving a vacancy on the shell. An electron from an outer shell (more energetic) drops down to fill the vacancy. This results in an emission of characteristic X-ray. Photoelectric effect represents anatomic structures with high X-ray absorption characteristics, radiopaque structures, tissue with high atomic number, or with high mass density (bone). It contributes to no image and increases patient dose.

2.1.2.2. Compton Scattering

Partial absorption with scatter also called Compton scatter means that part of the energy is absorbed by the tissue and part is scattered. Compton Effect increases with photon's energy, and is likely to occur with soft tissue and fairly high energy (high kVp) photons. It doesn't depend on the atomic number (probability for bone an atom is the same with soft tissue). Scattered radiation tends to degrade image quality and is the primary source of staff radiation exposure. Interaction of radiation with patient is presented in figure 2.2.

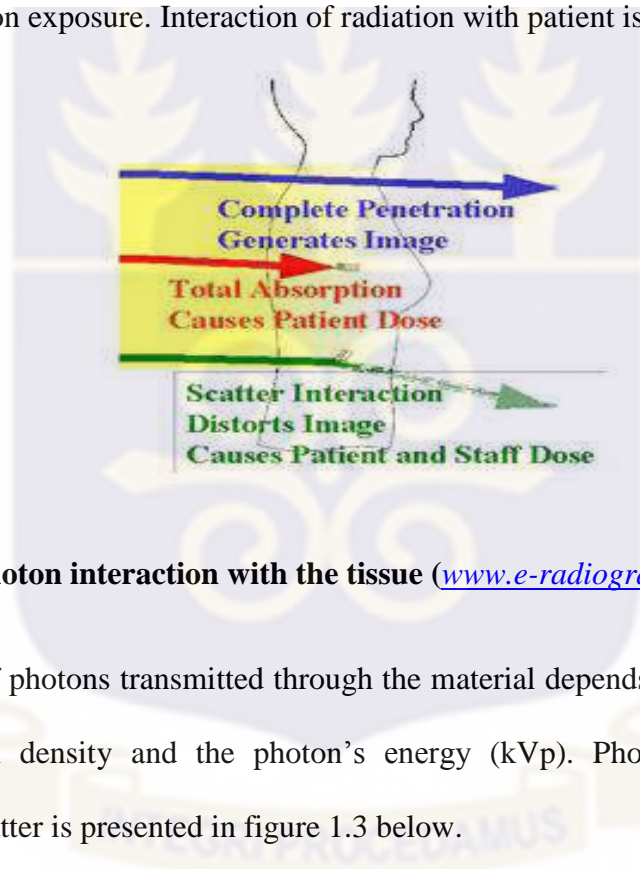


Figure 2.2: Photon interaction with the tissue (www.e-radiography.net)

The number of photons transmitted through the material depends on the tissue thickness, tissue electron density and the photon's energy (kVp). Photon attenuation passing through the matter is presented in figure 1.3 below.

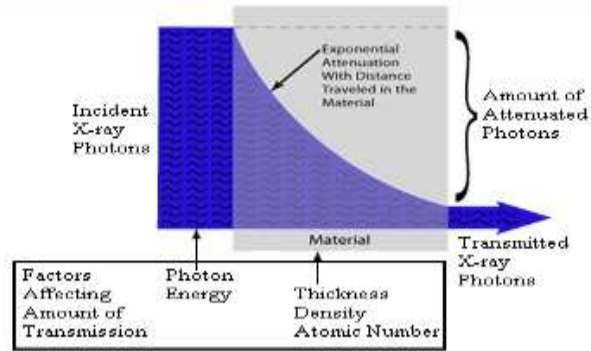


Figure 2.3: Exponential attenuation of photon energy in the material (Schuler, 2000)

The formula that describes this curve is Beer–Lambert’s Law defined as follow equation

(2.1):

$$I(x) = I_0 e^{-\mu x} \quad (2.1)$$

Where I is the initial intensity of the photon, μ is the linear absorption coefficient and x is the distance travelled.

2.2. Technology and Mode of Operation of the Fluoroscopy Machine

2.2.1 Fluoroscopic Imaging Chain

Fluoroscopy can be defined as a general method of radiographic examination by which real time image is produced on the fluorescent screen when the part to be examined is placed between the X-ray tube and fluoroscopic screen (schueler, 2000). It allows observation of gross physiology, which is concerned with motion of the heart, diaphragm and alimentary traction, follow through and so forth. The schematic of fluoroscopy chain is presented in figure 2.4.

The principal components required for the production and management of the fluoroscopic images are as follows:

- **X-ray generator:** produce electrical energy to the X-ray tube.
- **X-ray tube:** is located under the patient table for under couch fluoroscopy unit and above the table for over couch fluoroscopy unit. It is fixed to the fluoroscopic tower and convert electrical energy from the X-ray generator to X-ray

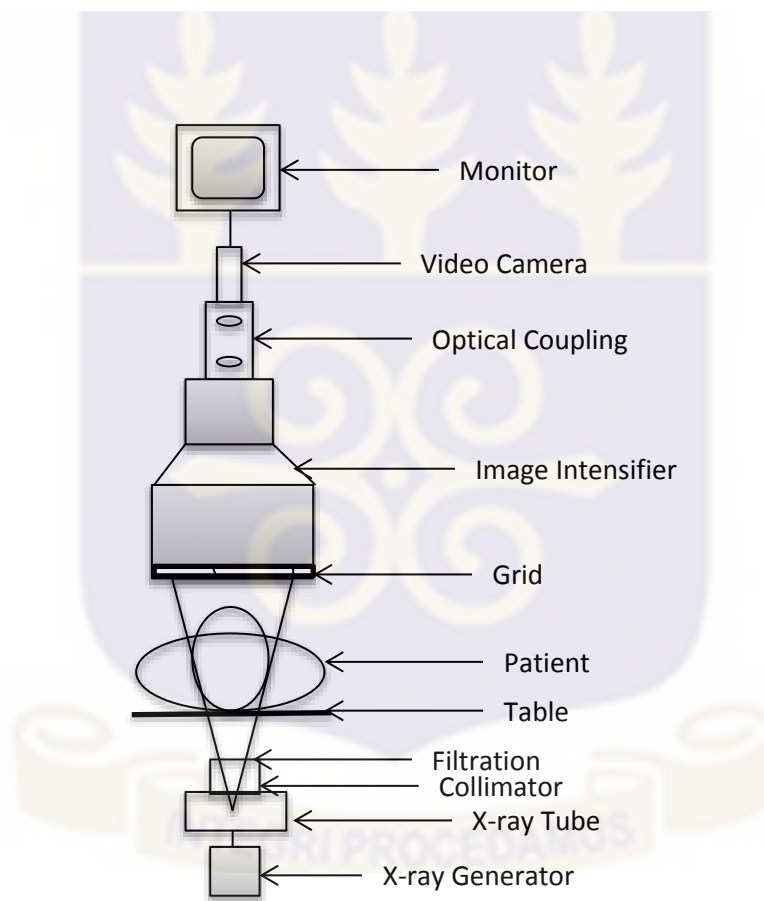


Figure 2.4: Schematic of the fluoroscopic imaging chain

- **Collimation:** is a device made of sets of shutters which is use to define with precision the area that will be irradiated. Collimation fundamental purpose is to prevent unwanted region of the body from being irradiated by coning down the area of interest.

This action thus reduces the overall patient and staff radiation dose. Proper collimation is important for high image quality.

➤ **Patient table and pad:** It is used to support the patient safely during the examination period.

➤ **Image intensifier**

The image intensification tube shown in figure 2.5 receives a small portion of the remaining X-ray beam, converts it into a visible light image and increases the image's brightness without increasing the patient dose.

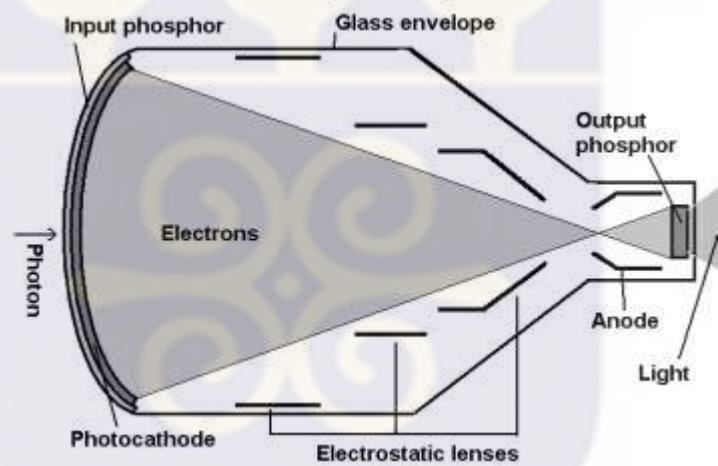


Figure 2.5: An image intensification tube

(Source: <http://www.usapa.army.mil/pdffiles/p350-59.pdf>.)

An image intensification tube has four basic components:

- **An input phosphor and photocathode:** used to stop high X-ray energy that exit from patient and convert it into a darkish visible light image. Then convert the visible light photon image into free electron.

- **Set electrostatic focusing lenses:** Focus the photoelectron comprising image by a low potential on the inside metallic coating of the tube so that it passes through the anode aperture. And secondly, provide different magnification levels for viewing.
- **An accelerating anode:** Accelerate the electron image to high speed by applying high voltage.
- **An output phosphor also made of CsI**

The electron image strikes the output phosphor and releases their kinetic energy in the form of massive amount of visible light photons. Thus, the output layer converts the electron to light necessary for visualization of the image.

2.2. Occupational Radiation Protection

Occupational exposure to ionizing radiation can occur in a range of industries, in mining and milling, in medical institutions, in educational and research establishments and in nuclear fuel cycle facilities. The term occupational exposure" refers to the radiation exposure incurred by a worker which is attributable to the worker's occupation and received or committed during a period of work (IAEA, 2003). Persons potentially exposed to radiation as a result of work to more than three tenths of the occupational dose limit are occupationally exposed workers (OEWs) or radiation workers.

2.3.1. Source of Occupational Radiation

In diagnostic and interventional radiology, workers are most likely exposed to three sources of radiations: scattered radiation, leakage radiation and direct beam show in figure 2.6.

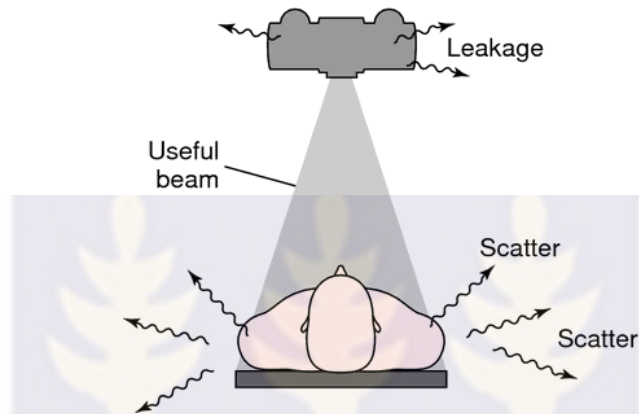


Figure 2.6: sources of occupational radiation exposure

(Source: <https://images.search.yahoo.com/scattered and leakage from x-ray.>)

- **Primary radiation or useful beam:** produce in the X-ray tube and it is used to irradiate the patient. For specific procedures worker's hands are exposed to the direct beam in the case of over couch fluoroscopes.
- **Leakage radiation:** are coming from the source assembly (including collimators). It should not exceed $1 \mu\text{Sv}$ per hour at one meter when the maximum kiloVoltage peak (kVp) is 125 – 150 kV and maximum milli Ampere (3 – 5 mA) or at every power rating specified by the manufacturer.
- **Scattered radiation:** arises from any object within the X-ray beam (including but to very limit extent, the air through which the primary X-ray beam passes). The patient is the most significant source of scatter radiation. The intensity of scatter is dependent on a number of factors, including the intensity of primary X-ray beam, the area of the X-

ray beam incident on the patient (patient entrance skin area) and the angle from which the primary beam at which scatter is assessed. Scattered radiation contributes to the majority of occupational exposure, especially during fluoroscopy.

2.3.2. Quantities used in Radiological Protection

In radiation measurement, three main categories of quantities are used. The quantities used to describe the radiation field called radiometric quantities, include energy fluence (rate), fluence (ϕ). The dosimetric quantities which includes, absorbed dose (D), exposure (X), and kerma (K) and the protection quantities are equivalent dose (H), effective dose (E), directional dose equivalent, etc.

2.3.2.1. Dose Quantities and Units used for Patient Dosimetry

➤ **Absorbed dose:**

The absorbed dose is the amount of energy imparted to the matter per unit mass of the irradiated material. The conventional unit is rad (Radiation Absorbed Dose) and the SI unit is the gray (Gy).

1Gy = 1J/kg = 100 rad. The rate at which an absorbed dose is received is called dose rate. The units are Gy/s, mGy/h and the most used is $\mu\text{Gy/h}$. the gray cannot be used to measure the relative biological effect on the body.

➤ **KAP (Kerma Area Product) for patient dosimetry**

Sometimes called DAP (Dose Area Product), is the dose integrated across the entire exposed field (dose multiplied by the area irradiated), usually expressed in $\text{Gy}\cdot\text{cm}^2$. It is

measured by fixing the KAP meter on the X-ray set. The KAP is independent of the distance from the source.

2.3.2.2. Dose Quantities for Occupational Exposure

The quantities recommended by ICRP for occupational dosimetry are protection quantities expressed in term of effective dose and equivalent dose (ICRP, 2007).

➤ Equivalent Dose

The equivalent dose is a quantity used to indicate the relative health effect caused by a specific type of radiation. It is the product of the absorbed dose in the volume of organ or tissue (T) $D_{T,R}$ and radiation weighting factor W_R and is expressed in equation (2.2).

$$H_T = \sum_R W_R D_{T,R} \quad (2.2)$$

The sum is performed over all types of radiation involved. The SI Unit of equivalent dose is Sievert (Sv). For diagnostic radiology ($W_R = 1$) effective dose is numerically equal to absorbed dose.

➤ Effective dose

Defined by ICRP publication 60 as a weighted sum of tissue equivalent doses and is expressed in equation (2.2).

$$E = \sum_T W_T H_T = \sum_T W_T \sum_R W_R D_{T,R} \quad (2.3)$$

W_T is the tissue weighting factor and represent also the contribution of individual organs and tissues to the overall radiation detriment $\sum_T W_T = 1$.

The effective dose is expressed using the Sv. It is the average over all the tissues of the human body and is probably the most useful way to express and compare the dose delivered by different imaging procedures.

These are not measurable quantities. The effective dose and equivalent dose for occupational exposure are assessed by using the operational quantities (ICRP, 2007a).

2.3.3. Operational Quantities for Individual and Area Monitoring

The operational quantities used for area monitoring of external exposure are: ambient dose equivalent $H^*(10)$ and directional dose equivalent $H'(0.07, \Omega)$.

The quantity used for individual monitoring is personal dose equivalent $H_p(d)$ which is defined as the dose equivalent in International Commission on Radiation Units and Measurements (ICRU) sphere (soft tissue) at an appropriate depth d below a specified point on the human body. To assess the effective dose, $H_p(10)$ with $d = 10$ mm is used, $H_p(0.07)$ with depth $d = 0.07$ mm for the dose to skin, the hands and the feet, and a depth $d = 3$ mm is used for monitoring the dose to the lens of eye ($H_p(3)$). Operational quantities are measurable using radiation monitoring devices, which are calibrated in terms of $H_p(10)$ and $H_p(0.07)$.

2.3.4. Radiation Effects and Radiation Protection Principles

2.3.4.1. Radiation Effects

X – ray is a form of ionizing radiation which once in the human body can interact with atoms and cause ionization in cells which may produce free radicals or direct effect that

can damage the Deoxyribonucleic Acid (DNA) or cause cell death. The adverse health effects of radiation exposure are classified into two types:

➤ **Deterministic effects**

Deterministic effect is defined as an outcome for which severity of the effect increases with dose and for which a threshold exists and are typically quite high. It is the result of a large part of cells kills/malfunction following high doses. Some examples are: skin erythema, hair loss, cataract, etc.

➤ **Stochastic effects**

Stochastic radiation effects involve either cancer in exposed individuals due to mutation of somatic cells or heritable diseases in their offspring due to mutation of reproductive (germ) cells. It is considered as chronic effect and caused by longer exposure relatively lower doses. The dose response model for stochastic effect is the linear-non-threshold (LNT) at low dose. The probability that cancer and heritable effects caused by radiation can occur increases with increment in the equivalent dose.

- **Risk of cancer**

The ICRP in publication 60 estimated cancer risk coefficient based on direct human epidemiological data (ICRP, 1990). Years later, the cancer risk coefficient at low dose and low dose rate were estimated based on many data such as occupational exposure (early Radiologist and Medical Physicist), medical overexposure, bomb victims, Inhabitants of high natural background areas, accidents, etc. Biological Effects of Ionizing Radiation (BEIR VII) committee combined radiobiological and epidemiological evidence concerning the Dose and Dose Rate Effectiveness Factor (DDREF) using data on solid cancer in Life Span Study (LSS) and life shortening in animals to choose the

modal value of DDREF as 1.5 with probabilistic uncertainties (BEIR, 2006). ICRP (2007) adopted the risk reduction factor of 2 for radiological protection to derive the nominal risk coefficient for all cancer given in table 2.1 below (ICRP, 2007a).

- **Risk of heritable effect**

The framework for the estimation of heritable risk adopted by ICRP was based on data from human and mouse. In publication 60, ICRP use another approach to heritable risk based on the concept of Doubling-Dose (DD) for disease – associated mutation (ICRP, 1990). In agreement with United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2008) and BEIR VII, ICRP gives an estimation of the genetic risk up to the second generation of about 0.2% per Gray (BEIR, 2006).

- **Nominal risk coefficients for cancer and heritable effects**

ICRP in publication 103 (2007) proposed risk coefficients values for human health effects (cancer and heritable effects) based on calculation of sex – averaged nominal risk coefficient seen in table 2.1 (ICRP, 2007a).

Table 2.1: Risk coefficients for stochastic effect proposed by ICRP ($10^{-2} Sv^{-1}$). (ICRP, 2007a)

| Exposed population | Cancer | | Heritable effects | | Total detriments | |
|--------------------|--------|------|-------------------|------|------------------|------|
| | 2007 | 1990 | 2007 | 1990 | 2007 | 1990 |
| Whole | 5.5 | 6.0 | 0.2 | 1.3 | 5.7 | 7.3 |
| Adult | 4.1 | 4.8 | 0.1 | 0.8 | 4.2 | 5.6 |

2.3.4.2. Radiation Protection Principle

The purpose of radiation protection is to control exposure to ionizing radiation in order to avoid deterministic effects and ensure that the likelihood of stochastic effects is kept below the unacceptable level. To achieve this objective, ICRP (2007a) recommended three basic principles of radiological protection which are: justification of the practice, optimization of protection and application of dose limitation.

➤ **Justification of practice:** for any procedure that involves ionizing radiation, the benefits must be well established and accepted by both medical practitioner and society at large. ICRP publication 103 ICRP, (2007a) state as a principle of justification that “any decision that involves the radiation exposure situation should do more good than harm” and (ICRP, 2007b) in publication 105 said that, “in the case of the individual patient, justification normally involves both the referring medical practitioner who refers the patient (example of patients physician/surgeon) and the radiological medical practitioner under whose responsibility the examination is conducted”. In fluoroscopy guided intervention the responsibility rest with the interventionist.

➤ **Optimization:** find a way to do the examination at a lower dose while maintaining efficacy and accuracy. In optimization process the likelihood of incurring exposures, the number of people exposed and their individual doses should be kept as low as reasonably achievable. It should be considered from the design stage of equipment and installation, through operation to decommissioning and waste management.

➤ **Dose limits:**

Dose limitation is defined in the BSS as “the value of effective dose or equivalent dose to individual from controlled practices that shall not be exceeded”. For occupational

exposure, it is applied to the sum of effective dose from external sources. Table 2.2 present the new dose limits for individuals occupationally exposed.

Table 2.2: ICRP’s recommendations for dose limits (ICRP, 2007; ICRP, 2013)

| Effective Dose Limits | |
|---------------------------------------|--|
| 20 mSv per year averaged over 5 years | |
| 50 mSv in a single year | |
| Equivalent Dose Limits | |
| Lens of the eye | 20 mSv per year averaged over 5 years |
| | 50 mSv in a single year |
| Skin | 500 mSv per year averaged over 1 cm ² area of skin regardless of the area exposed |
| Extremities | 500 mSv per year |

2.3.4.3. Dose Constraint

The use of dose constraint is highly recommended in optimization of protection. For occupational exposure, dose constraint is that value of individual dose from a source (always lower than annual dose limit) serving as upper bound on the predicted dose in optimization of protection for that source. In the case that the boundary is exceeded, meaning that protection is not optimized, an investigation should be conducted. For better optimization, an investigation level should be established in term of effective dose or equivalent dose received monthly. The monthly investigation level will serve as an alert to review the level of protection to that period of time and it should not exceed annual dose limit or dose constraint when it is extrapolated to a year.

In 2000, the World Health Organization (WHO) recommended an investigation to be carried out when monthly exposure reaches 0.5 mSv for effective dose, 5 mSv for eye lens, or 15 mSv for the extremities (WHO, 2000). With the review of annual eye lens dose, Duran *et al* (2013) proposed for interventional cardiologists a new investigation level of 2 mSv per month.

2.4. Strategies to Reduce Radiation Risk to Staff

It is the responsibility of all staff members working in radiation to take measures that will enhance radiation protection and safety in the department. Techniques used to reduce patient dose, will reduce the scatter radiation to operators and thus decrease occupational radiation dose. Cardiovascular and Interventional Society of Europe summarized dose reduction techniques generally applied in interventional cardiology procedures in table 2.3 below (Miller *et al*, 2010).

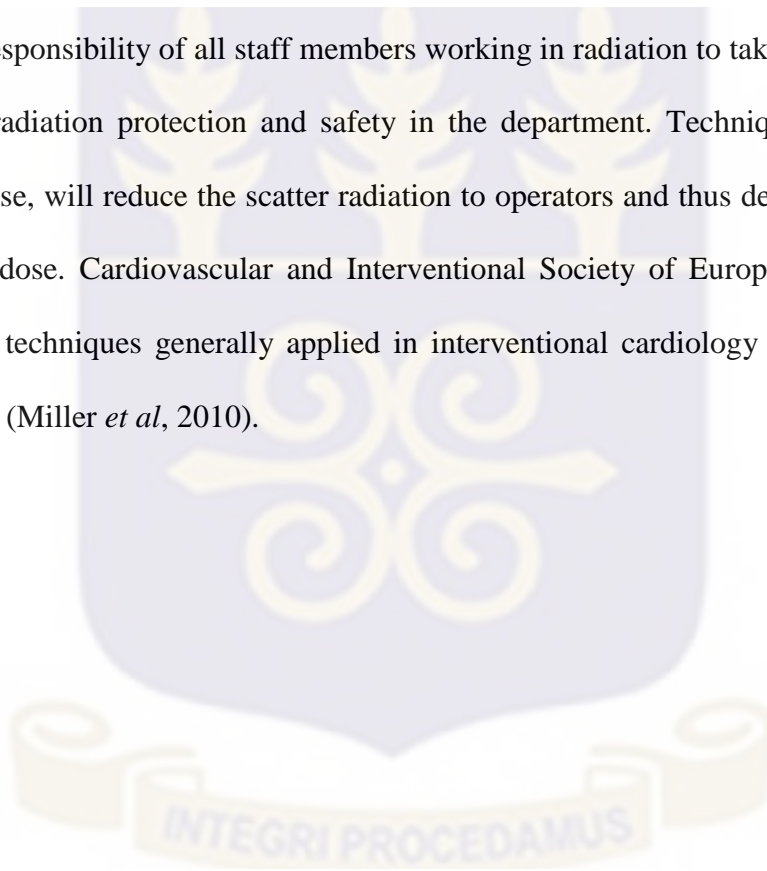


Table 2.3: Dose reduction techniques commonly used fluoroscopy procedures
(Miller *et al*, 2010)

| Techniques used in interventional cardiology | Corresponding functions |
|--|--|
| Minimize use of fluoroscopy time and use low fluoroscopy mode | Reduce staff and patient dose |
| Number of fluorographic images | Reduce staff and patient dose |
| Image-chain geometry | Reduce patient dose |
| Collimation of the radiation field | Decrease the level of scatter dose |
| Medical staff position in a low-scatter area | Reduce staff dose |
| Wear protective shielding | Reduce radiation dose to eye lens and other organs |
| Fluoroscopic imaging equipment comply with International Electrotechnical Commission (IEC, 2010) | Dose-reduction technology is incorporated into the imaging systems |
| Obtain appropriate training provided by professional bodies | Increase awareness of radiation protection and dose reduction |
| Wear personal dosimeter | Know and monitor your own dose |
| Diagnostic reference levels | Monitor clinical practice and radiation dose |

2.4.1. Practical Application of Optimization of Protection

The basics tools of occupational radiation protection are time, distance and shielding.

2.4.1.1. Time

Fluoroscopy time should be minimized by screening only when necessary. The health care personnel should limit the amount of time spent close to the radiation source.

2.4.1.2. Distance

The shorter the distance, the higher is the exposure. The longer the distance, the lesser is the exposure. The health care professional should avoid direct beam and keep the maximum distance from the patient.

2.4.1.3. Shielding

Shielding is the key for staff dose reduction and it is applied at three levels: architectural shielding, equipment – mounted shields and personal protective shield (Christopoulos *et al.*, 2015). The most important component of personal protective shielding is the lead apron which must be worn by all staff present in the fluoroscopy room. The common thickness of lead apron used in fluoroscopy room is 0.25 mm on the back and 0.35 mm on the front or 0.25 mm on the back and 0.5 mm on the front. Depending on the X – ray energy (kV setting) and the lead equivalent thickness of the apron, the lead apron may reduce the dose by 85% - 99% (Bushberg *et al.*, 2012). The use of lead glasses is strongly recommended to interventional Cardiologists and Radiologists and can reduce the eye exposure of the operator by 85% to 90% (Kim *et al.*, 2009). A separated thyroid shield is

also recommended for workers in X – ray room. Most catheterization laboratories is equipped with a ceiling suspended screens which contain lead impregnated in plastic or glass and a table mounted lead curtain which provide effective attenuation. Roguin *et al* (2012) and Reeves *et al* (2015) reported brain tumor at the left side of the head of interventional cardiologists, saying that it was caused by radiation exposure.

2.4.2. Education and Training Programs

Training is a basic requirement for healthcare professional in terms of optimization of radiation protection. It increases awareness of the risk of radiation and enhance the use of protective measures in order to reduce exposure.

In interventional procedures where, high dose of radiation is used, proper education and training is highly recommended for all staff (cardiologists, nurses, technologist, etc.) at the time of employment and as part of continuing education program. In 2009, Vano *et al* (ICRP publication 113) included training in radiological protection as part of Quality Assurance (QA) program, highlighted its importance and give specific recommendations for interventional procedures (Vano *et al.*, 2009).

Georges *et al* (2009) provided training materials to improve radiation protection and safety in interventional procedures showing the successful impact of training program on dose reduction.

2.5. Individual Monitoring

Personal monitoring is considered as the gold standard for radiation surveillance in intervention procedures (Christopoulos *et al.*, 2015). Personal dosimeters must be adequately accurate in different exposure conditions, small and lightweight for the

convenience in use such that it will not affect staff performance in exercising their task. The individual monitoring of health professional can be achieved using two types of dosimeters: passive dosimeters and active dosimeters.

2.5.1. Passive dosimeters

They give information on the personal dose after processing. Film, thermo luminescent dosimeters (TLDs), optically stimulated luminescent (OSLs) badges are some examples. They are small, lightweight, do not require power and well package for the comfort of staff. These are the most used in personal dosimetry around the world. The reading process makes the dosimetry system suitable to verify compliance and not convenient for optimization (ICRP, 2018).

2.5.2. Active Personal Dosimeters (APDs)

They are also called electronic dosimeters. They provide instant information of the dose when it is exposed to radiation. It is suitable for optimization and analysis of dose by procedure. The direct feedback on the dose give opportunities to staff to take actions within a procedure if needed and evaluate the effectiveness of the protective action taken. It also facilitates auditing of the wearing of APDs during procedures and the study the correlation between occupational and patient exposure (ICRP, 2018). For photon energies between 20 and 150 keV and spectra used for fluoroscopy procedures, the dosimetry system must meet IEC standard (IEC, 2012) and internationally accepted guidance (ICRP, 2010; IAEA, 2014). It must be simple, reliable and efficient to execute required action (ICRP, 2018).

2.6. Assessment of Occupational Exposure

2.6.1. Effective Dose Assessment

The accuracy and precision on the dose assessment depend on the location of the dosimeter on the body. In fluoroscopy guided procedures, workers are partly shielded. Therefore, single dosimeter placed over the lead apron will overestimate the dose, the same way a single dosimeter placed under the lead apron will underestimate the dose because it doesn't consider the unshielded part of the body such as head, hands, legs etc. therefore a correction factor should be applied to the reading of the dosimeters for better estimation of effective dose (Siiskonen *et al.*, 2007).

2.6.1.1. Double Dosimetry Approach

All personnel working in radiation area must be monitored. In interventional procedures, ICRP (2000) recommends the use of two dosimeters (one worn on the trunk of the body inside the lead apron and another outside the lead apron on the thyroid collar at the left side). This has been approved by the National Council on Radiation Protection (NCRP, 2010) as it provides the best estimation of the effective dose. The algorithm used to combine the reading of the two dosimeters is in the form of equation 2.4.

$$E = \alpha H_U + \beta H_o \quad (2.4)$$

Where E is the effective dose, H_U and H_o are the personal dose equivalent $H_p(10)$ measured under the apron and over the apron on the collar respectively, α and β are the factors to be applied to the dosimeter reading. Over the years many couples of α and β has been proposed by many authors, but there is not international agreement on which one should be used. Among the entire double dosimetry algorithm tested by Jarvinen *et*

al. (2008) within the European Coordinated Network for Radiation Dosimetry (CONRAD), ICRP (2018) found α and β combination proposed in the Swiss Ordinance (2008) to be the best to estimate the effective dose.

2.6.1.2. Single Dosimetry Approach

Although the double – dosimetry approach provides better accuracy, it has some disadvantages:

- No international agreement on the algorithm that should be use. This makes the comparison of the effective dose difficult to interpret.
- No reliability in wearing two dosimeters correctly and consistently by the interventionists.
- The higher cost of two dosimeters.

A single dosimeter worn under the lead apron gives the dose received by radiosensitive organs at the trunk. the monthly reading of these dosimeters is often below the detection level, making this monitoring technique poor and limited in providing information. Many studies have shown that there is no significant difference between double – dosimetry and one dosimeter worn over the lead apron corrected by a factor (ICRP, 2018).

Based on studies of the relationship between Hp (10) from the over apron dosimeter and Monte Carlo simulation or direct measurements using an anthropomorphic phantom, Martin and Magee (2013) proposed an algorithm of effective dose for staff performing fluoroscopy procedures in radiology, cardiology and interventional radiology. The algorithm defines in equation 2.5 was accepted and proposed by ICRP publication 139 in 2018.

$$E = 0.1 H_0 \quad (2.5)$$

2.6.2. Assessment of Equivalent Dose to the Lens of the Eye

Before ICRP (2011) new recommendation of eye lens dose limit, the eye lens dosimetry was hardly performed by clinicians, who were assuming that the limit was too high (150 mSv) and that the whole-body monitoring was enough to provide reliable eye lens dose. In 1992, ICRU recommended the use of the personal dose equivalent $H_p(3)$ to assess the eye lens dose (ICRU, 1992). This operational quantity was found suitable for the eye lens dosimetry, but dosimeters calibrated in term of $H_p(3)$ are non-available in many countries. ICRP in publications 103 and 117 recommended the use of $H_p(0.07)$ for monitoring of the lens of the eye for photon exposures (ICRP, 2007; ICRP, 2010). IAEA (2013) suggested that $H_p(0.07)$ can be used to approximate $H_p(3)$ for photon radiation field and $H_p(10)$ can only be considered when the mean energy of the photon spectrum reaching the dosimeter is more than 40 keV. IAEA (2014), ISO (2015) and International Radiation Protection Association in Paris (IRPA, 2017) have provided the monitoring procedure for the lens of eye. Clerinx *et al* (2008) and Martin (2009) based on Monte Carlo study, proposed a factor between the equivalent dose $H_p(0.07)$ read from a dosimeter worn at the collar level and eye lens dose.

Personal monitoring program consist in monitoring, recording, evaluating and reporting the radiation dose received by individuals occupationally exposed to radiation in a department. All the staff exposed to radiation must be monitored at the international standard, especially those performing fluoroscopic procedures.

CHAPTER THREE

3.0. Material and Method

This chapter will focus on the description of the study area, sample size, materials and methods used for data collection and analysis.

3.1. The Study Area

This study was conducted in the biggest referral hospital in Ghana. KBTH is situated at $5^{\circ} 32' 16.2''$ north, $0^{\circ} 13' 38.67''$ west, 5.5374 latitude and $- 0.2274$ longitude, Guggisberg Avenue of Ablekuma Sub – locality in Accra Metropolis District, Greater Accra Region of Ghana. Figure 3.1 present the location of KBTH in Ghana.



Figure 3.1: Location of KBTH in Greater Accra Region

Korle Bu means the valley of the Korle lagoon. It was founded on 9th October 1923 as a general hospital to address health issues of the population. KBTH leads three centers of excellence, the National Cardiothoracic Centre (NCTC), the National Plastic and Reconstructive Surgery and the National Centre for Radiotherapy and Nuclear Medicine

and has 17 clinical and diagnostic departments/units. Because of sophisticated procedures provided in various field, KBTH attract patients from all over Ghana and West Africa Sub-region and sometimes from other countries in Africa.

In KBTH, fluoroscopy guided procedures are conducted in the Radiology Department, Accident Department and NCTC. Because of some factors such as the limited time allocated for the study, limited number of equipment available and the limited access to the departments, this study was focused in the Radiology Department and NCTC.

3.1.1. Radiology Department of KBTH

The Radiology Department is well equipped with different modalities system to attend to in and out patients. The systems include X-ray machines used for general radiography such as chest, pelvis and spine etc., one over couch fluoroscopy unit for special diagnostic examination like barium studies, Hysterosalpingogram (HSG), Intravenous Urogram (IVU), myelogram sometime for interventional procedure (biliary drainage) etc., three ultrasound machine, X-ray machine for emergency cases, one Computed Tomography (CT) scanner, Magnetic Resonance Imaging (MRI) scanner and portable X-ray at surgical department. The department transfers nine (9) Consultant Radiologists and 18 in training, among whom four (4) are assigned for fluoroscopy examinations on the monthly basis. The fluoroscopy room has two trained radiographers and two nurses.

Fluoroscopy examination room is very spacious 6 m x 6.8 m (40.8 m²). The walls are made up of concrete material of about 30 cm width. Console room is separated from examination room by wall of 28.5 cm width and 220 cm height and had a glass screen lead equivalent. The entrance door to the room is made up lead sheet of 3 mm and had a warning light on top of the door which illuminate when the X-ray is on. The room is

equipped with two screens (one in the examination room for Radiologists and one in the console room for Radiographers) and functional air conditioner

The fluoroscopy unit is SHIMADZU FLEXAVISION (CE 0197) over couch as shown in figure 3.3. It was manufactured in Japan in February 2012. Model: Collimator type R – 30 H and serial number 3Z0FF7D22045, the maximum tube kVp 150 and Al equivalent is 1.0 mm. The unit is powered by one generator model Servo – REG with serial number 130451, manufactured the 24th April 2013. The standard distance from the source to bed is one meter.



Figure 3.2: Over couch fluoroscopy Machine at the Radiology Department, KBTH

3.1.2 National Cardiothoracic Centre (NCTC)

The NCTC shown in figure 3.3 was founded in January 1989 by Dr. Frimpong – Boateng. It is a very dedicated center with a 30 beds ward, 2 operating theatres, a laboratory, radiology, echocardiography services, cardiac catheterization laboratory and a renal dialysis unit. Staff members comprise a team of seven cardiothoracic surgeons assisted by Cardiologists, Anesthetists, cardiovascular Perfusionists, nurses, Technologists etc.

NCTC offer their services to patients from all over the country and receives regular referrals from Nigeria, Sierra Leone, Gambia, Liberia, Togo etc. (Edwin et al, 2011).



Figure 3.3: Outlook of the actual NCTC at KBTH

Cardiac Catheterization Laboratory (Cathlab) is used in modern cardiology and cardiac surgery for diagnostic and treatment of many heart diseases without opening the heart of the patient. The new cathlab was installed in October 2016 and inaugurated on Wednesday 4th January 2017 by the former Ghana President John Mahama. The fluoroscopy unit at the cathlab in figure 3.4 is the type Siemens (Artis Zee/Zeego) Megalix catplus 125/40/90 – 121 GW, model N° 10144181 and serial number 640041673. The maximum tube voltage is 125 kV – IEC 60613 and total filtration is 0.8 mm Al/80 kV. It was manufactured in February 2016 in Germany.



Figure 3.4: Internal view of Cathlab with Siemens biplane fluoroscopy unit.

3.2. Sample Size

All operators who conducted fluoroscopically guided procedure during the period of data collection in Radiology Department and NCTC were the sample size of this study. A total of four (4) Radiologists and four (4) Cardiologists were monitored.

3.3. Materials

A questionnaire was been issued to assess the level of radiation protection practices in the cathlab. The Pirhana was used for Quality Control (QC) on equipment, KAP meter was used to record patient dose for fluoroscopy procedures conducted in radiology department, electronic dosimeters for personal monitoring, survey meter for area monitoring.

3.3.1. Questionnaire

A set of questions were prepared for the purpose of interview. Based on these questions, an interview was done between the investigator and the chief nurse (who is in charge of the cathlab), Cardiologists and Radiologists. This was done in order to collect information on radiation protection and safety measures practice in the laboratory to prevent the risk of ionizing radiation both for patient and workers. The questions had two main parts: the first part was about the general information on the equipment and the second focused on the information regarding the radiation protection of the personnel.

3.3.2. Piranha

Pirhana is a Radiation to Information (RTI) package used for an instant X – ray Quality Assurance (QA) solution. It is an all in one multimeter that can be connected to a

computer wireless or via Universal Serial Bus (USB). It works with the diagnostic RTI software ocean 2014, which is used to display, record and report all the measurements, waveforms and facilitate the reading on a screen. The Piranha was used in this work for the quality control test of the fluoroscopy units at Radiology Department and NCTC. The Piranha version 5.5 with serial number CB2 – 15020088, was manufactured in Sweden and calibrated the 11th March 2015 by SWEDAC. ACKREDICTERING. The Piranha was connected to a computer with an Ocean 2014 software installed on the window 7 systems for reading (Figure 3.5). Table 3.1 presents the specifications of the piranha used.



Figure 3.5: Setup of QC tools (piranha and ocean 2014 installed on a computer)

under the X – ray system

Table 3. 1: Specifications of the Piranha for radiography / fluoroscopy

| Elements | Specifications |
|-------------------------|---|
| Dose | Range: 0.1 nGy–1500 Gy*, Inaccuracy: 5% |
| Dose Rate | Range: 1 nGy/s*–320 mGy/s, Resolution: 0.2 nGy/s*, Inaccuracy: 5% or 0.25 nGy/s |
| Total Filtration | 60–120 kVp, 1–90 mm Al or 2 mm Cu |
| kVp | Range: 35–160 kVp, Minimum Dose Rate: 0.1 μ Gy/s, Inaccuracy: 1.5% |
| HVL | Range: 0.72–13 mm Al, Minimum Peak Dose Rate: 0.1 μ Gy/s, Inaccuracy: 10% or 0.2 mm Al. Quick HVL in one exposure |
| Total filtration | Range: 1.0–90 mm Al, Minimum Dose Rate: 0.1 μ Gy/s Inaccuracy: 10% or 0.3 mm Al |
| Time | Range: 0.1 ms–2000s, Resolution: 0.5 ms, Inaccuracy: 1% or 0.5 ms |

3.3.3. Kerma Area Product Meter

The Kerma X – plus is made of a transparent ion chamber, model 120 – 131 and serial number 01A04042 (50 – 150 kVp, Class II – type B), with a separated reader with “10 – digit LCD “Single Line Display”, model 120 – 210 with serial number 01E004774. It was manufactured by IBA dosimetry service. The ion chamber was fixed on the collimator of

the X – ray unit at the radiology department to measure DAP for patient dose monitoring.

Figure 3.6 below shows the Kerma X – plus package used for this study.

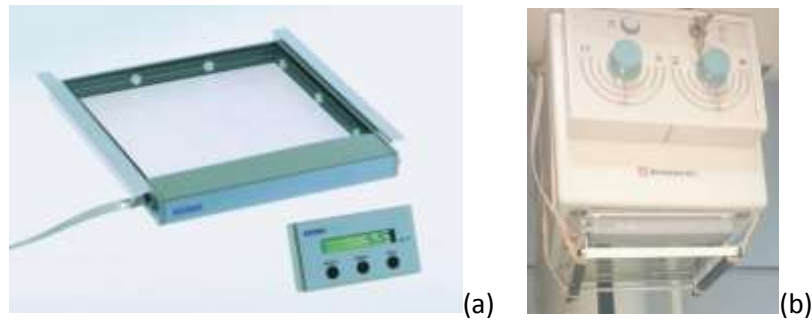


Figure 3.6: (a) The Kerma X – plus with the separated reader and (b) the ion chamber fixed on the X – ray tube in radiology department.

3.3.4. Electronic Personal Dosimeter (EPD)

Four (4) labeled EPD of type EPD MK 2.3 manufactured by Thermo Electron Corporation were used for this study to measure the dose to the personnel. The corresponding serial numbers of the EPDs were 00179975, 00178174, 00070491, 00179958. The EPD is a direct reading dosimeter suitable to use in occupational dosimetry according to the Radiation Protection and X – ray ordinance (FO75KOM06A/Datasheet EPD MK, 2014). Personal dosimeters is used to measure personal depth dose equivalent $H_p(10)$ and the personal surface dose equivalent $H_p(0.07)$ both from photons (X-rays and gamma radiation) and beta radiation. It can be attached to the clothing with a clip mounted on the housing well display in figure 3.7 below.



Figure 3.7: Electronic Personal Dosimeters used for this study

These dosimeters were calibrated at the Secondary Standard Dosimetry Laboratory (SSDL) of GAEC to check the accuracy on the reading during the study. The Calibration set up is shown in figure 3.8 below.

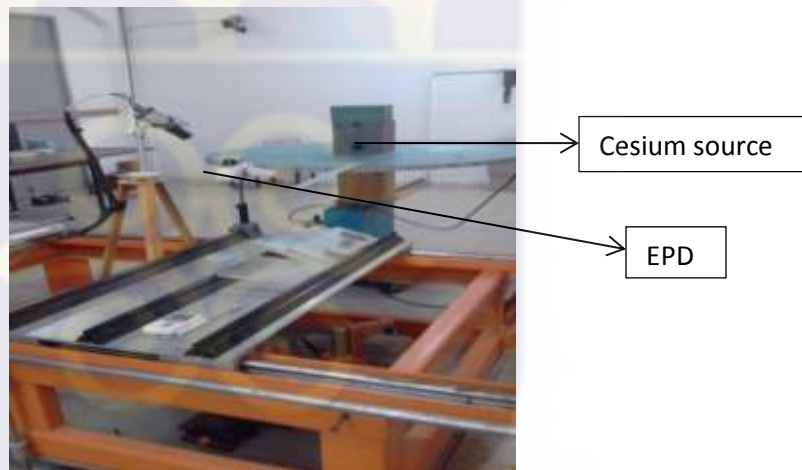


Figure 3.8: Calibration setup in SSDL at GAEC

3.3.4.1. Measurement Method

The radiation detector is made of PIN diodes in which charges are induced by radiation (electron – hole –pairs). The measurements of charges in terms of electric current constitute the measurement of the dose rate from which the value of the dose can be derived by adding the time (is stored in the dosimeter and can be read out via an infrared

interface). The thin beta - window is used to measure beta radiation because of its low penetrating power. The detailed picture of the EPD used for this study is shown in figure 3.9 below.

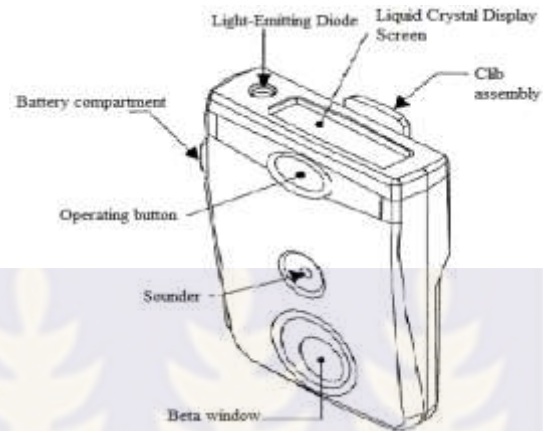


Figure 3.9: Typical personal dosimeter (Source: www.helmholtz-muenchen.de/awst)

3.3.4.2. EPD MK 2+ Radiological and Environmental Specifications

The Thermo Scientific Mk2+ EPD is perfect for organizations, utilities, agencies, and research laboratories to monitor employee dose and dose rates. The radiological and environmental key features of these instruments as stipulated in the user manual are presented in tables 3.2 and table 3.3 respectively.

Table 3.2: EPD MK 2+ Radiological Specifications

| Components | Details |
|--------------------------|---|
| Display Units | Sv and rem OR scaled in Sv and cGy (with prefixes) |
| Dose Display and Storage | 0 μ Sv to > 16 Sv (0 mrem to > 1600 rem) |
| Display Resolution | 1 μ Sv (0.1 mrem), up to 10 Sv |
| Storage Resolution | 1/64 μ Sv (=1.5 μ rem) |
| Energy Response | Photon: Hp(10): [All ref. 137Cs]: $\pm 50\%$ 15 keV to 17 keV; $\pm 20\%$ 17 keV to 1.5 MeV; $\pm 30\%$ 1.5 MeV to 6 MeV; $\pm 50\%$ 6 MeV to 10 MeV |
| | Photon: Hp(0.07): [All ref. 137Cs]: $\pm 30\%$ 20 keV to 6 MeV; $\pm 50\%$ 6 MeV to 10 MeV |
| | Beta: Hp(0.07): $\pm 30\%$ 250 keV to 1.5 MeV (ref. 90Sr/90Y) |
| Angular Response | Hp(10) 137Cs $\pm 20\%$ up to $\pm 75^\circ$; Hp(10) 241Am $\pm 50\%$ up to $\pm 75^\circ$; Hp(0.07) 90Sr/90Y $\pm 30\%$ up to 55° |
| Accuracy | Hp(10) 137Cs $\pm 10\%$; Hp(0.07) 90Sr/90Y $\pm 20\%$ |
| Dose Rate Linearity | Hp (10) 137Cs: $\pm 10\%$ <0.5 Sv/h (<50 rem/h); $\pm 20\%$ 0.5 to 1 Sv/h (50 to 100 rem/h); $\pm 30\%$ 1 to 2 Sv/h (100 to 200 rem/h); $\pm 50\%$ 2 to 4 Sv/h (200 to 400 rem/h); Between 4 and 50 Sv/h continues to accumulate dose at a rate > 1 Sv/h |
| | Hp (0.07) 90Sr/90Y: $\pm 20\%$ <1 Sv/h (<100 rem/h); Between 1 Sv/h and 50 Sv/h continues to accumulate dose at a rate > 1Sv/h |

Table 3.3: EPD MK 2+ Environmental Specifications

| Components | Details |
|-----------------------|---------------------------------------|
| Operating Temperature | -10°C to +50°C (+14°F to +122°F) |
| Humidity | 20% to 90% RH, non-condensing |
| Vibration | IEC 1283: 2g, 15 minutes, 10 to 33 Hz |

3.3.5. Dose Rate Meter

The dose rate meter presented in figure 3.10 is the type PM1703MO – 2. It is a personal combined radiation detector/dosimeter manufactured by Polymaster with serial number 2160498.



Figure 3.10: Dose rate meter used in this study

This instrument is designed to measure ambient Dose Equivalent Rate (DER) $H^*(10)$ of gamma and X – ray radiation, to detect and locate radioactive materials and alerting the user with audible, visual and vibration alarms.

Figure 3.11 and table 3.4 show the design and characteristics of the dose rate meter respectively according to the operational manual.

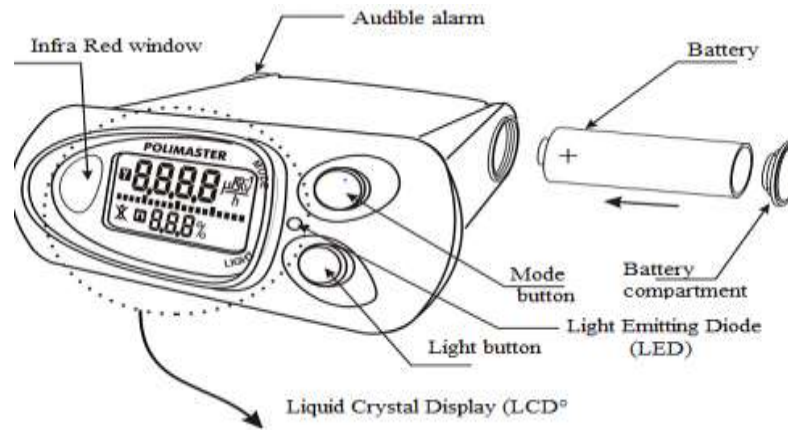


Figure 3.11: Functional parts of the dose rate meter (Source: www.Polimaster.com)

Table 3.4: Characteristics of the dose rate meter

| Specifications | PM 1703MO – 2 |
|--|---|
| Detector | |
| - gamma search | CsI(Tl) |
| - gamma measurement | GM tube |
| Sensitivity | |
| - for ^{137}Cs , $\pm 20\%$ | 85 (s-1)/(Sv/h) (1.0 (s-1)/(R/h)) |
| - for ^{241}Am , no less | 130 (s-1)/($\mu\text{Sv/h}$) (1.3 (s-1)/($\mu\text{R/h}$)) |
| Energy range | 0.033 - 3.0 MeV |
| Time of measurement | 0.25 s |
| Dose Rate | 0.01 Sv/h - 10 mSv/h (1 R/h - 1000 mR/h) |
| Maximum permissible intrinsic relative error of DER measurement in measurement range | $\pm 30\%$ in measurement range 0.1 $\mu\text{Sv/h}$ - 10 Sv/h (10 $\mu\text{R/h}$ - 1000 R/h) |
| Alarm type | visual, audio, vibration |
| Operating temperature | -30°C to 50°C (-22°F to 122°F) |

3.4. Software

3.4.1. Microsoft Excell

The software used for the data analysis in this study was Microsoft excel 2010 version 14.0 included in Microsoft office 2010 installed on a window 7 system.

Excel provides functions to solve statistical, engineer and financial problems and it is used to display data as line graphs, histograms and charts. It supplies pivot tables and scenario manager that can be used to section data in order to view dependencies between variables (Greg, 2007). It can also be used for numerical methods to solve differential equations in mathematics and physics. Figure 3.12 shows the interface of excel 2010 running on window 7.

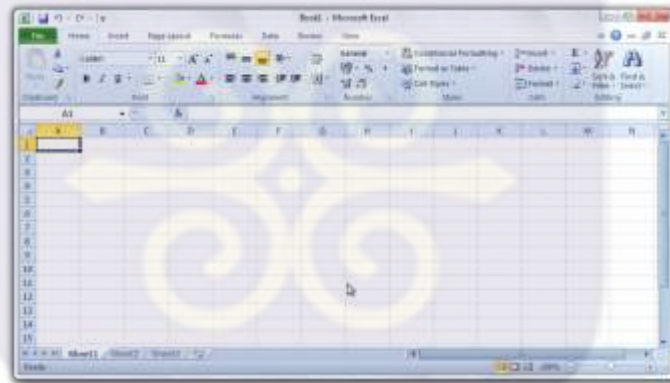


Figure 3.12: Microsoft excell 2010 running on window 7

3.4.2. Simple Geo

Simple Geo version 4.3.3 was used in this work. It is an interactive solid modeler used to implement geometries for particles transport problems. It provides a flexible and easy platform to create modes via drag and drop, and also debugging facilities based on stochastic and deterministic methods for validation of the created geometry. In other

word Simple Geo offers an interface where the created geometry is visualized so that corrections and modifications can be immediately done. The created geometry in Simple Geo can be exported to ray tracing packages such as FLUKA, Monte Carlo N particle (MCNP), etc. (Theis *et al.*, 2006). The following figure 3.13 presents a geometry created with Simple Geo.

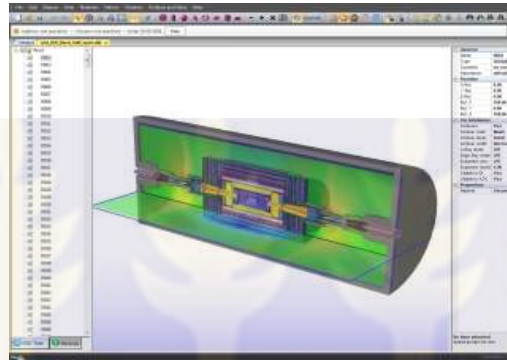


Figure 3.13: Simple Geo interface with an example of geometry created (Theis *et al.*, 2006).

3.4.3. Monte Carlo N Particle (MCNP)

MCNP is a general purpose, continuous energy, generalized – geometry and time dependent code developed by Los Alamos National Laboratory (LANL). It is designed to simulate fission and particle interaction (neutron, photon, electron or coupled neutron / electron / photon) over a broad range of energies. It found its application in many areas such as radiation shielding, medical physics, dosimetry and radiation protection, nuclear reactor modeling, etc. it is a three-dimensional geometry with flexible source and tally options, interactive graphics, and support for both sequential and multi – processing computer platforms. The latest version is MCNP 6 package which gives abilities to

import unstructured mesh geometries from the finite element code, to model complete atomic relaxation emissions, etc.

3.5. Methods

Approval letter to conduct this research were provided by the College of Basic and Applied Science and also the KBTH Scientific and Technical Committee (KBTH-STC). The ethical clearance was obtained from the Institutional Review Board (IRB) of KBTH.

3.5.1. Quality Control (QC) Tests

In order to verify that the fluoroscopy equipment was performing consistently, standard QC tests were undertaken before all measurements. The following are the parameters which were checked: beam collimation, kVp accuracy and reproducibility, time reproducibility, half value layer, leakage test, mAs linearity and exposure reproducibility and compared with the standard limits provided by Nuclear Regulatory Authority of Ghana (NRA, 2016). The room size has been measured using the tape meter. The distance between the X –ray source and the table were 1 m.

3.5.1.1. Beam Collimation

This test is performed to check if the X – ray beam coincides with the light field, because the radiation field may be shifted away from the area of clinical interest. This was achieved by placing a sheet of paper under the radiation field and height (8) coins of 20 pesewas were positioned strategically on the corners (in and out) of the sheet of paper and some images were taken. The accuracy on the collimation was checked by measuring the distance of the shifting of coins on the image using the meter provided at the

computer screen. Figure 3.14 shows one image of the collimation check. The distance measured was subtracted from the diameter of the coin (23 mm).



Figure 3.14: Radiograph from the beam collimation check

3.5.1.2. Reproducibility Test

For every X – ray machine, some parameters such as kV, exposure time and exposure should be reproducible. To assess the reproducibility, the machine was set at 80 kV and 10 mAs. The exposure was repeated three (3) times and the results were registered in the Ocean 2014 software. For all these parameters, the coefficient of variation should be less than 5% and this was calculated as follows (NRA, 2016):

$$\text{Coefficient of Variation (COV)} = \frac{\text{Standard deviation}}{\text{Average}} \times 100\% \quad (3.1)$$

3.5.1.3. kVp and Exposure Time Accuracy

For kV, the test was performed at tube voltage 70 kV up to 115 kV at the highest tube current (250 mA and 110 ms). The readings were registered and the percentage of error was automatically calculated by Ocean 2014 according to equation (3.2) (find the results on Appendix 5).

$$\text{Percentage kVp error} = \frac{(V_0 - V_s)}{V_s} \times 100 \quad (3.2)$$

Where V_0 is the measured value and V_S is the set value. The percentage kVp error should lie within $\pm 6\%$ (NRA, 2016).

The machine was set at 80 kVp, 250 mA and the first time at 8 ms. The procedure was repeated for different time 63 ms, 100 ms, and 0.125 s. The percentage error should lie within $\pm 10\%$ (NRA, 2016). It has been calculated according to equation (3.3) below.

$$\text{Percentage timer error} = \frac{(T_0 - T_S)}{T_S} \times 100 \quad (3.3)$$

Where T_0 is the measured value and T_S is the set value.

3.5.1.4. mAs Linearity

To perform this test, the parameters of the machine were set at 80 kV and at first 2.5 mAs. The exposure, time kV was recorded and the value of exposure / tube current (mGy / mAs) was calculated. This procedure was repeated for 20 mAs, 32 mAs, and 40 mAs. The maximum and minimum values of (mGy / mAs) were recorded and the linearity was found according to equation (3.4). It should be less than 10% (NRA, 2016).

$$\frac{\text{Max-min}}{\text{Max+min}} \leq 10\% \quad (3.4)$$

3.5.1.5. Half Value Layer (HVL)

The determination of HVL was obtained directly from the Piranha at one exposure when the setting of the machine was 80 kVp and 250 mA, and 0.11 s. this value should be more than 2.3 mm Al (NRA, 2016).

3.5.1.6. Leakage Test

The tube output rate free in air was measured using the dose rate meter (survey meter) at one-meter distance from focal spot to front, back, right and left of the X – ray tube when the collimator is completely shut at maximum kVp (125 kVp) and 25 mAS. The values should be less than 1 mGy/h.

3.5.2. Dose Monitoring

The four dosimeters used for measurements were labeled (chest 1, chest 2, neck 1, and neck 2) in order to reduce errors during the readings. All measurements were performed within one month at Radiology Department and two months at the Cathlab. For every type of procedures requiring the presence of the operator near the patient, dose to the workers were measured. Two electronic dosimeters (thermo fisher) were issued for every operator conducting the procedure. One dosimeter was fixed under the lead apron at chest level and the second one, over the lead apron on the thyroid shield at neck level. For patient dose, the KAP meter was fixed on the X-ray tube (Radiology). The following parameters were recorded in both departments:

- The type and the number of the procedure performed by each operator.
- The patient dose (DAP) per procedure.
- The screening time of each procedure.
- The personal equivalent dose $H_p(10)$ from each dosimeter was recorded daily and $H_p(0.07)$ for the dosimeter worn over the lead apron at neck level.
- The protective equipment available in the room and the protective actions.

3.5.3. Scatter Radiation Study in the Examination Room

Cathlab was modeled according to the measured parameters using Simple Geo.

Height 290 cm, length 740 cm, breadth 400 cm and size of the lead glass 100 cm x 315 cm are presented in figure 3.15.

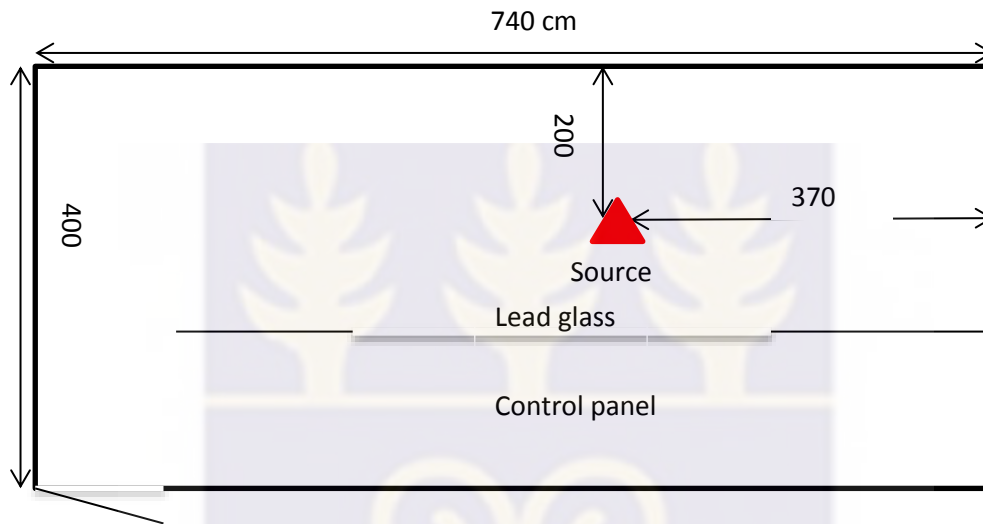


Figure 3. 15: CathLab dimensions

Scattered radiation dose was measured by irradiating an improvised plastic rectangular shape container with rounded corners filled with water used as phantom to simulate a standard patient (50 Cm length, 30 cm width and 22 cm height). This is a good representative of human trunk. Dose rate was measured at 160 Cm height from the floor at each strategic angles (0° , 90° , 180° , 270°) as illustrated in figure 3.16 at 1m from the isocenter. The projection angles of the tube at which the data were collected were Left Anterior Oblique (LAO) 30° , Right Anterior Oblique (RAO) 30° and Antero Posterior (AP) 0° presented in figure 3.17. At each point three measurements were taken and the average was calculated in order to reduce errors.

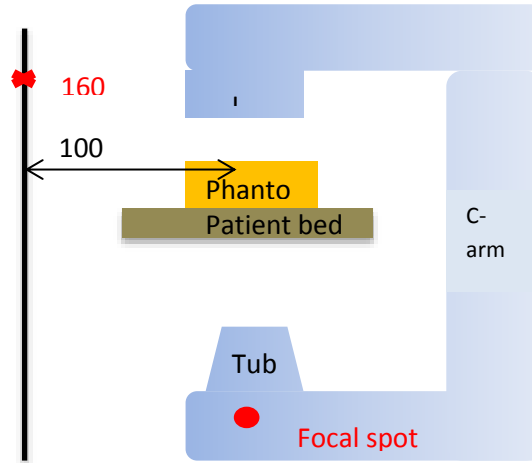


Figure 3.16: Schematic of the side view of measurement set - up

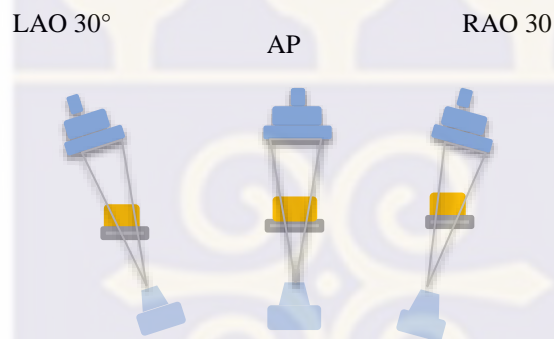


Figure 3.17: Schematic of the top view of the measurement set-up showing the point of measurements at different angles at 1m from the isocenter.

3.5.4. Data Analysis

Microsoft excel was used to analyze data and presented them in tables and graphs. The correlation between the KAP values recorded and staff dose was done by regression analysis to determine the P-value, R^2 and the possible equation which can be used for prediction.

3.5.4.1. Whole – Body Dose Calculation

In agreement with regulatory requirement, staff dose monitoring is mostly done by the use of one dosimeter worn at chest/waist level under the lead apron and the recorded value from the dosimeter represents the effective dose (ICRP, 2000). The methodology for personal monitoring used in this study is the double dosimetry (one dosimeter worn in lead at waist level and another out lead at neck level on the thyroid collar) method recommended by NCRP (1995) and ICRP (2000) for both Radiologists and Cardiologists. Many algorithms have been developed combining dose recorded from the two dosimeters, but there is no yet an international consensus about which algorithm to use. The table 3.5 presents some algorithm proposed by different authors for effective dose calculation both for single dosimeter and double dosimeters.

Table 3.5: Algorithm proposed for effective dose calculation with thyroid collar
[adapted from Jarvinen et al. (2008) and ICRP publication 139 (2018)]

| Source | Dosimetry Type | Effective dose estimation |
|---------------------------------|----------------|--|
| NCRP Report 122 (NCRP, 1995) | Single | $H_p(10)_{Over} \times \frac{1}{21}$ |
| Martin and Magee (2013) | Single | $0.1 \times H_p(10)_{Over} *$ |
| NCRP Report 122 (NCRP, 1995) | Double | $0.5H_p(10)_{Under} + 0.025H_p(10)_{Over}$ |
| Swiss Ordinance (2008) | Double | $H_p(10)_{Under} + 0.05 H_p(10)_{Over} *$ |
| Clerinx <i>et al</i> , 2008 | Double | $1.64H_p(10)_{Under} + 0.075H_p(10)_{Over}$ |
| Chida <i>et al</i> , 2013 | Double | $0.89 H_p(10)_{Under} + 0.075H_p(10)_{Over}$ |

(*) represent the algorithms used in this work which was recommended in publication 139 (ICRP, 2018) for single and double dosimetry using the protective collar. $H_p(10)_{under}$ is the deep dose calculated from the dosimeter worn at waist level under the lead apron and $H_p(10)_{over}$ is the dose calculated from the dosimeter worn at neck level above the apron. The value of equivalent dose used in this calculation was obtained by the following equation 3.5.

$$H_p(10)_{real} = \mathbf{k} * H_p(10)_{read} \quad (3.5)$$

Where k is the calibration factor, $H_p(10)_{read}$ is the value read from dosimeters.

The same equation was applied for $H_p(0.07)$

3.5.4.2. Eye Lens Dose Calculation

The international recommendation of the eye lens monitoring is the use of personal dosimeters calibrated in terms of $H_p(3)$. Because of the non – availability of such dosimeters, many authors established the correlation between $H_p(0.07)$ read on the dosimeter worn on the thyroid collar and the eye lens dose. Some coefficients found in literature are presented in the following table 3.6.

Table 3.6: Ratio (eye lens / Thyroid) doses [adapted from Carinou *et al.* (2015)]

| References | Ratio (eye lens/Thyroid) | Geometry Equipment |
|-----------------------------|--------------------------|--------------------|
| Covens <i>et al</i> (2007) | 0.73 | under couch tube |
| Lie <i>et al</i> (2008) | 0.75 * | |
| Clerinx <i>et al</i> (2008) | 0.75 * | |
| Hausler <i>et al</i> (2009) | 0.68 | |
| Buls <i>et al</i> (2002) | 1.22 | Over couch tube |
| Suliman <i>et al</i> (2008) | 1.46 * | |

(*) are the equations used for eye lens dose estimation for both Radiologists and Cardiologists depending on the geometry of the equipment used in this work.

Monthly dose received by each worker monitored was calculated by summing the daily dose over the whole month using equation (3.6).

$$E_M = \sum_{i=1}^n E_i \quad (3.6)$$

Where E_M is the monthly dose, E_i is dose received per procedure.

For cardiologists the annual dose was estimated by calculating the mean of three-monthly dose and multiply by twelve (12).

$$\text{Annual effective dose} = \frac{\sum_{i=1}^3 E_{Mi}}{3} \times 12 \quad (3.7)$$

3.5.4.2. Workload

The workload is defined differently depending on whether it is for a device or an individual. For a device, it is the weekly radiation output expressed in mA-minute per

week. It can also be defined in term of working time or amount of work that is expected or assigned to an individual for a period of time. This gives an idea of the time a worker spends under radiation whether weekly, monthly or annually. It can also be expressed in term of number of procedures. In this study, the workload has been calculated in term of total time spent under the radiation and also the number of procedures performed by each Cardiologist over a period of 2 months in cathlab. The monthly average workload was calculated in order to estimate the annual workload for each worker.

3.5.4.3. Risk Assessment

The risk assessment was calculated using the risk coefficient values provided by ICRP 2007 recommendations given in table 2.1 in the previous chapter. The cancer, heritable effect, total detriment and lifetime risk have been estimated for each Cardiologist working with radiation.

The general equation used for cancer and heritable effect risk is expressed as follow in equation 3.8:

$$\text{Annual Risk (AR)} = E_{\text{annual (Sv)}} \times \text{Nominal Risk Coefficient} \quad (3.8)$$

Where E is the annual effective dose in Sievert (Sv) and the nominal risk coefficient in Sv^{-1}

The total detrimental effect can be estimated by summing the annual cancer risk and annual heritable effect risk.

3.5.5. Monte Carlo Simulation

The dimensions of the examination room were taken using tape measure. The location of the couch, X-ray tube with respect to the room was located. Dose rate measurement at a distance of 100 cm from the couch to the focal spot of the tube was measured using a survey meter for verification of the computational model.

Simple Geo was used to model the X-ray room, phantom and the X-ray source using the already taken dimensions. The model was out put into Monte Carlo input file for simulation as shown in Appendix 7. The model was verified for accuracy using the measured dose rate in air at 100 cm. An X-ray spectrum was generated for the simulation at 100 kVp, 12 degree tungsten anode and 2.5 mm Al using SpekCalc (spectrum generation software).

The Monte Carlo input file was simulated on a computer with a processing speed of 3 GHz. 1.9×10^9 photon particles were tracked for a reasonable computational time and output accuracy. Photon dose rate deposited per particle mesh in the X-ray room was tallied for the output results.

The output of radiation dose rate/particle in the room was plotted in a contour to illustrate the spread of radiation using GNUPlot (plotting software version 5.2, patchlevel 4).

CHAPTER FOUR

4.0. Results and Discussions

This chapter presents the QC results of the equipment and the compliance with the regulatory standard in Ghana. It also presents the overall research finding from the assessment done and comparison of workers parameters between the two departments, two X-ray tube geometry. The finding was also compared with other studies and recommendations of ICRP, IAEA and NCRP.

4.1. Basic Elements of Radiation Protection in Both Department

At the Radiology Department among the six (6) staff members working in fluoroscopy room, four (4) responded to the questions (one radiographer and three radiologists) and in cathlab, the chief nurse, the chief cardiologist and three other cardiologists were the respondents. Table 4.1 presents the summarized results of the interview made showing the actual state of radiation protection in both departments.

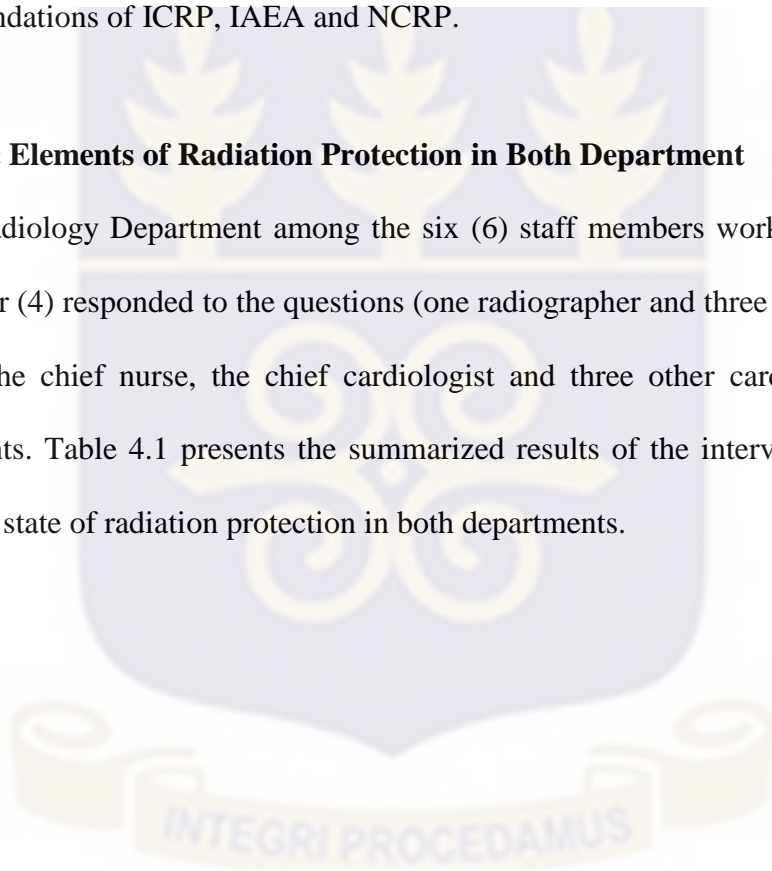


Table 4.1: Status of radiation protection measure in both departments

| In | Protective measures | Radiology | Cardiology |
|----|--|------------------|-------------------|
| | Tube Geometry | Over couch | Under couch |
| | Presence of warning light | Yes | Yes |
| | Lead apron | Yes (100%) | Yes (100%) |
| | Thyroid shield (0.35 mm) | Yes (100%) | Yes (100%) |
| | Lead glasses | Yes (25%) | No |
| | Lead gloves | No | No |
| | Other protective equipment (ceiling suspended screen and lead drap) | Not available | Yes (full use) |
| | Use of collimation | No | No |
| | Medical physicist | Yes | No |
| | Refresher training of workers | No | No |
| | Quality assurance program | No | No |
| | Radiation Protection Officer | No | No |
| | Regular QC on the machine | No | No |

radiology department, no personnel had received refresher training on radiation

protection. They have acknowledged the presence of a Medical Physicists. Survey on radiation protective clothing showed the availability of six (6) lead aprons: two (2) one side aprons (0.35 mm), two wraps around apron (0.35 mm front and 0.25 mm back), two (2) one side aprons (0.5 mm), and one skirt and one shirt (0.35 mm front and 0.25 mm back). Other available protective clothing includes three (3) thyroid collar of 0.5 mm, two (2) pairs of lead glasses and one pair of lead gloves are for Radiologists. The ceiling suspended screen and lead drape were not available. Radiologists expressed the inconvenience in using lead gloves due to the small size of catheter and syringes used during procedures even though their hands are most often exposed to the direct beam. The radiation protection measures to reduce patients and operator doses such as (use of collimation, reduce number of images and frame, etc.) were not applied. The record keeping in Radiology Department needs more attention.

At the NCTC, Cardiologists and Nurses affirmed that they have received training on radiation protection during their general training, but they have not received any refresher training in course of their work. This may be due to the absence of a Radiation Protection Officer (RPO) or Medical Physicist, Quality Assurance program in the department. Therefore, no frequent QC test is performed on the equipment. In term of personal protection equipment, the department is well equipped with one lead curtain (0.5 mm) fixed on patient bed, the ceiling suspended screen lead equivalent (0.5 mm), eight (8) thyroid collar of 0.5 mm and a total of ten (10) lead apron: four (4) one side apron of 0.5 mm use by nurses, four (4) wrap around apron of 0.5 mm front and 0.25 mm back, one side apron of 0.35 mm and one wrap around skirt and shirt of 0.5 mm front and 0.25 mm back. But no lead glasses or gloves were available. Every worker has a well labeled TLD

badge provided by Lumina Dosimetry Services. They wear inside the lead apron at waist level. But these TLDs had never been read since the starting of the new cathlab in October 2017 till the end of this study. Thus, there was not personal dose record in the department. Patient's information and doses details are well recorded and well kept on digital form (computer, CDs and external hard disk) and also hard copies.

In general, table 4.1 reveals the critical aspects of radiation safety program are not practiced in both departments. These departments require the presence of a radiation protection officer to assure continuous training of workers on radiation protection. The QC and radiation survey around the workplace are performed by the regulatory authority during their inspection. This study has been useful both for workers and at the departmental level in the way that it has brought awareness of radiation exposure to the workers. This leads to some practice of protective measures at worker level and will contribute to the implementation of continuous personal monitoring in both departments.

4.2. Quality control results

4.2.1. Over couch Fluoroscopy in Radiology Department

Peak tube voltage, screening time and tube outputs measured when set tube voltage and mAs are 80 kV and 2.5 mAs respectively are shown in table 4.1 with the calculated deviations.

Table 4.2: kVp, time and output reproducibility test.

| Measuring quantities | 80 kV, 2.5 mAs | | | Mean | COV% |
|----------------------|----------------|--------|--------|--------|-------------|
| Actual kV | 75.21 | 75.79 | 75.62 | 75.54 | 0.30 |
| Time (ms) | 31.60 | 31.61 | 31.61 | 31.60 | 0.03 |
| Output (μ Gy) | 363.40 | 363.70 | 365.30 | 364.13 | 0.20 |

Peak tube voltage sets and measured together with calculated deviations used to assess accuracy are shown in table 4.3.

Table 4.3: Tube voltage accuracy

| kV accuracy | | | | | | |
|-------------|-------------|-------------|-------------|-------------|-------------|----------|
| Set kV | 70 | 80 | 90 | 100 | 110 | 115 |
| Actual kV | 69.19 | 77.9 | 87.25 | 97.46 | 106.89 | 111.55 |
| D kV | 0.81 | 2.1 | 2.75 | 2.54 | 3.11 | 3.45 |
| % DkV | 1.16 | 2.63 | 3.06 | 2.54 | 2.83 | 3 |

For tube voltage set at 80 kV, the set values of mAs, measured values of exposure and calculated values of exposure / mAs are presented in table 4.4.

Table 4.4: mAs linearity

| mAs linearity (80 kV) | | | | |
|-----------------------|--------|----------|------------|--------|
| m A s | 2.5 | 20 | 32 | 40 |
| Exposure (mGy) | 0.1085 | 0.8409 | 1.307 | 1.652 |
| mGy / m A s | 0.0434 | 0.042045 | 0.04084375 | 0.0413 |

From the values calculated in table 4.4, the mAs linearity is calculated as indicated in equation 4.1:

$$\text{The mAs linearity} = \frac{\text{Max}-\text{min}}{\text{Max}+\text{min}} = \frac{0.0434-0.04084375}{0.0434+0.04084375} = \mathbf{0.03} \quad (4.1)$$

A total of seven (7) QC tests were performed on the over couch fluoroscopy tube used at the Radiology Department. The calculated deviations for each test and the standard acceptable deviations provided by Ghana Nuclear Regulatory Authority are presented in the following table 4.5.

The room size of 40.8 m² is far greater than the minimum required. The beam collimation deviation was found between 5 – 6.10 mm which was below the acceptable deviation of 10 mm. The tube voltage accuracy (3.10 %), mAs linearity (0.03) are both below the tolerance $\pm 6\%$ and 0.1 respectively. The reproducibility of tube voltage, time and exposure were 0.3%, 0.03%, and 0.2% respectively. These are less than the tolerance $\pm 5\%$. The HVL measured at 80 kV was 3.17 mm Al which is greater than the minimum (2.3 mmAl) recommended and the leakage was not detectable by the measuring instrument meaning that it was less than 1.00 mGy /h.

Table 4.5: Summary of the results

| Parameter | Deviation of Fluoroscopy Machine (Measurement) | Acceptable Deviation (NRA, 2016) | Remarks |
|--|---|---|----------------|
| Room Size (Sq. metre) | 40.8 m ² | ≥ 25.0 m ² | Pass |
| kVp Accuracy | 3.10 % | ≤ ±6.0 % | Pass |
| mAs Linearity | 0.03 | ≤ 0.10 | Pass |
| Collimation Accuracy | 6.10 mm | ≤ 10.0 mm | Pass |
| HVL (mm Al) @ 80kV | 3.17 mm Al | ≥ 2.3 mm Al | Pass |
| Tube Leakage at 1m | - | < 1.00 mGy/h | - |
| Tube Voltage | | | |
| Reproducibility @ (10mAs,80 kV) | 0.30 % | COV ≤ 5.0 % | Pass |
| Exposure Reproducibility @ (10 mAs,80 kV) | 0.2. % | COV ≤ 5.0 % | Pass |
| Exposure Time | | | |
| Reproducibility @ (10 mAs,80 kV) | 0.03 % | COV ≤ 5.0 % | Pass |

(-) means that, radiation no detectable.

4.2.2. Under couch Fluoroscopy in Cathlab

The measured tube voltage, time, output and the calculated deviations are presented in table 4.6 below.

Table 4.6: Voltage, time and output reproducibility test

| Measuring quantities | Values | | | | Mean | COV(%) |
|----------------------|--------|--------|--------|--------|--------|--------------|
| Actual kV | 77.38 | 77.55 | 77.38 | 77.49 | 77.45 | 0.10% |
| Time (ms) | 270.00 | 270.00 | 270.50 | 270.50 | 270.25 | 0.10% |
| Output (μ Gy) | 467.20 | 464.70 | 469.60 | 469.60 | 467.77 | 0.43% |

The console reading, measured tube voltage and the deviation are given on table 4.7 below.

Table 4.7: Tube voltage accuracy

| kVp accuracy | | | | | | |
|--------------|--------------|-------------|-------------|--------------|--------------|--------------|
| Console kV | 77.30 | 78.70 | 81.00 | 81.00 | 93.80 | 94.40 |
| Actual kV | 77.77 | 75.79 | 80.54 | 84.10 | 98.57 | 100.10 |
| D kV | -0.47 | 2.91 | 0.46 | -3.10 | -4.77 | -5.70 |
| % DkV | -0.61 | 3.69 | 0.57 | -3.83 | -5.09 | -6.04 |

A summary of five (5) QC tests was performed on the under couch (C-arm) used in cathlab. The measured room size, the calculated deviations and the standard acceptable deviations by Ghana Nuclear Regulatory Authority are presented in the following table 4.8 (NRA, 2016).

Table 4.8: Summary of the results of QC test

| Parameters | Deviation of X-ray Machine (Measurement) | Acceptable Deviation (NRA, 2016) | Remarks |
|---------------------------------|---|---|----------------|
| Room Size (Sq. metre) | 29.30 m ² | ≥ 25.0 m ² | Pass |
| kVp Accuracy | 6.04 % | ≤ ±6.0 % | acceptable |
| HVL (mm Al) | 3.64 mm Al | ≥ 2.3 mm Al | Pass |
| Tube Leakage at 1m | No detectable | < 1.00 mGy | pass |
| Tube Voltage | 0.10 % | COV ≤ 5.0 % | Pass |
| Reproducibility | | | |
| Exposure Reproducibility | 0.10 % | COV ≤ 5.0 % | Pass |
| Exposure Time | 0.43 % | COV ≤ 5.0 % | Pass |
| Reproducibility | | | |

The room size of about 30 m² is greater than the minimum required. The tube voltage accuracy (±6.04%) was slightly higher than the requirement (±6%) but is acceptable. The reproducibility of tube voltage, time and exposure were 0.1%, 0.43%, and 0.1% respectively. These are less than the tolerance ±5%. The HVL measured at 80 kV was 3.64 mm Al which is greater than the minimum (2.3 mmAl) recommended and the leakage were not detectable by the measuring instrument meaning that it was less than 1.00 mGy /h.

These results show that, the two fluoroscopy machines are functioning well and the measurement taken can be reliable.

4.3. Patients and Radiologists Dose in Radiology Department

Radiation dose to radiologist was evaluated for 8 different types of diagnostic procedures carried out on 118 patients. The number of patients per type of procedure is presented in table 4.9.

Table 4.9: Summary of procedures and dose measurements

| Procedures | Abbreviations (performed by) | Number of procedures | Frequency of procedures |
|-----------------------------------|---|---------------------------------|------------------------------------|
| Hysterosalpingography | HSG (RAD 2 &3) | 74 | 63.8 |
| Retrograde Urethrogram | RUG (RAD 1) | 26 | 22.4 |
| Mituring Cysto-Urethrogram | MCUG (RAD 1) | 9 | 7.7 |
| Fistulogram | FIST (RAD 4) | 3 | 2.6 |
| Myelogram | (RAD 4) | 1 | 0.9 |
| Sialogram | (RAD 4) | 1 | 0.9 |
| Barium Meal | BM (RAD 4) | 2 | 1.7 |
| TOTAL | | 116 | 100 |

*RAD 1, 2, 3 & 4 means Radiologist 1, 2, 3 & 4

Table 4.9 shows that the most performed procedure was HSG with 63.8 % followed by RUG (22.4 %) and MCUG (7.7 %). Because of the high number of procedures, HSG procedures were conducted by two radiologists (RAD 2 and RAD 3). RUG and MCUG procedures were performed by one radiologist (RAD 1) and other procedures such as

barium meal, barium enema, myelogram, sialogram and fistulogram also called special cases in the department were conducted by one Radiologist (RAD 4). These procedures however, are not frequent.

4.3.1. Patient Dose and Fluoroscopy Time

The mean, median and range of patient dose (KAP) and fluoroscopy time of each type of procedure performed in radiology department are presented in table 4.10.

Table 4.10: Mean, median and range values of KAP and fluoroscopy time for each procedure.

| Procedures | KAP (Gy.cm ²) | | | Time (min) | | |
|------------------------------------|---------------------------|--------|-------------|------------|--------|-----------|
| | Mean | Median | Range | Mean | Median | Range |
| RUG | 6.7 | 5.6 | 3.5 – 16.8 | 0.7 | 0.6 | 0.3 – 1.6 |
| MCUG | 13.9 | 13.4 | 2.2 – 23.7 | 1.8 | 2.0 | 0.4 – 3.1 |
| RUG +MCUG | 40.7 | 41.0 | 37.1 – 44.1 | 1.5 | 1.5 | 1.2 – 1.9 |
| H S G | 6.0 | 5.7 | 1.9 - 14.4 | 0.7 | 0.6 | 0.2 - 2.5 |
| FIST | 35.0 | 30.2 | 8.7 – 66.1 | 1.9 | 1.4 | 1.4 – 3.0 |
| Myelogram and Sialogram | 25.6 | 10.3 | 10.3–40.8 | 3.4 | 1.9 | 1.9 – 4.8 |
| Baruim meal | 41.1 | 21.5 | 21.5–60.8 | 7.2 | 3.5 | 3.5– 10.9 |

The lowest fluoroscopy time range are [0.3 – 1.6] min and [0.2 – 2.5] min and the corresponding patient dose range are [3.5 – 16.5] Gy.cm² and [1.9 – 14.4] Gy.cm² were recorded for RUG and HSG procedures respectively. This can be attributed to the fact that those procedures are simple, fast and require the lowest number of image acquisition

(between 2 – 4 images). This observation is contrary to combined RUG + MCUG, FIST, myelogram and sialogram procedures which have almost the same time range and with high patient dose. The high patient dose recorded can be the result of the high number of image acquisition obtained during these procedures. Barium meal was found to be the lengthier procedure administering the highest dose to the patients. This procedure is performed on babies, so the length depends on how stable the baby is and require many image acquisitions than screening mode. A good example shown in this table was performed in 10.9 minutes and the recorded KAP was 60.7 Gy.cm² on a ten months baby female. A total of 16 images and 95 frames were recorded for this specific procedure without collimation.

In general, patient dose and fluoroscopy time are not uniformly distributed. Table 4.10 shows that patient dose varies with different type of procedures, not necessary with the fluoroscopy time. Also, for the same procedures, these two quantities vary for different patient. This observation lets conclude that patient dose depends on many other factors such as the complexity in patient anatomy, patient size, etc.

4.3.2. Radiologist Dose and Workload

Table 4.11, 4.12, 4.13 and 4.14 represent the daily number of procedures, fluoroscopy time, the estimated effective dose using three (3) different methods (one dosimeter out leads, one outside lead and double dosimetry) and the eye lens dose of RAD1, RAD2, RAD3 and RAD4 respectively. It also represents the number of days each radiologist performed procedures during the data collection.

Table 4.11: Estimated daily effective dose (using three different methods) and eye lens dose to RAD 1

| | Procedures | Number of cases | Time (min) | Single in E1 (μSv) | Single out E1(μSv) | Double E3 (μSv) | E eye (μSv) |
|--------------|-----------------|-----------------|------------|---------------------------------|---------------------------------|------------------------------|--------------------------|
| Day 1 | RUG | 2 | 2 | 1 | 6.6 | 4.3 | 96.4 |
| | MCUG | 1 | 1.1 | | | | |
| Day 2 | RUG | 3 | 1.2 | 1 | 5.8 | 3.9 | 84.7 |
| | RUG+MCUG | 1 | 1.5 | | | | |
| | MCUG | 1 | 2.2 | | | | |
| Day 3 | RUG | 2 | 2.4 | 1 | 2.9 | 2.5 | 42.3 |
| Day 4 | RUG | 3 | 1.2 | 1 | 3.2 | 2.6 | 46.7 |
| | RUG+MCUG | 1 | 1.2 | | | | |
| Day 5 | RUG | 2 | 1.7 | 0 | 6.3 | 10.2 | 92.0 |
| | MCUG | 1 | 3.1 | | | | |
| Day 6 | RUG | 2 | 1.7 | 0 | 1.3 | 0.7 | 19.0 |
| Day 7 | RUG | 1 | 0.7 | 1 | 1.8 | 1.9 | 26.3 |
| | MCUG | 1 | 1.9 | 0 | 1.7 | 0.9 | 24.8 |
| Day 8 | RUG | 3 | 2.4 | 2 | 8.1 | 6.1 | 118.3 |
| | MCUG | 2 | 2.9 | | | | |

Table 4.12: Estimated daily effective dose (using three different methods) and eye lens dose to RAD 2 for HSG procedures

| | Number of cases | Time (min) | Single in E1 (μSv) | Single out E2 (μSv) | Double E2 (μSv) | E eye (μSv) |
|--------------|--------------------|---------------|------------------------------------|-------------------------------------|---------------------------------|-----------------------------|
| DAY 1 | 3 | 1.2 | 3 | 4.7 | 5.4 | 68.6 |
| DAY 2 | 4 | 2.5 | 6 | 12.7 | 12.4 | 185.4 |
| DAY 3 | 5 | 2.7 | 1 | 5.8 | 3.9 | 84.7 |
| DAY 4 | 4 | 2.1 | 1 | 3.6 | 2.8 | 52.6 |
| DAY 5 | 2 | 0.7 | 1 | 3.2 | 2.6 | 46.7 |
| DAY 6 | 5 | 2.9 | 2 | 8.9 | 6.5 | 129.9 |

Table 4.13: Estimated daily effective dose (using three different methods) and eye lens dose to RAD 3 for HSG procedures.

| | Number of cases | Time (min) | Single in E1 (μSv) | Single out E1 (μSv) | Double E2 (μSv) | E eye (μSv) |
|--------------|--------------------|---------------|------------------------------------|-------------------------------------|---------------------------------|-----------------------------|
| DAY 1 | 3 | 1.2 | 3 | 3.1 | 4.5 | 45.3 |
| DAY 2 | 1 | 0.9 | 1 | 4.2 | 3.1 | 61.3 |
| DAY 3 | 6 | 1.9 | 1 | 4.4 | 3.2 | 64.2 |
| DAY 4 | 3 | 2.5 | 1 | 10.3 | 6.2 | 150.4 |
| DAY 5 | 2 | 0.6 | 1 | 7.1 | 4.5 | 103.7 |
| DAY 6 | 3 | 2.2 | 4 | 14.4 | 11.2 | 108.0 |

Table 4.14: Estimated daily effective dose (using three different methods) and eye lens dose to RAD 4.

| Procedures | Time | Single in | Single out | Double | E eye |
|-----------------------|-------|-----------------------|-----------------------|-----------------------|--------------------|
| | (min) | E1 (μSv) | E2 (μSv) | E3 (μSv) | (μSv) |
| Barium meal | 10.9 | 13 | 116.2 | 71.1 | 1696.5 |
| Sialogram | 1.9 | 1 | 1.10 | 1.6 | 16.0 |
| Fistulogram | 5.1 | 7 | 87.6 | 50.8 | 1279.0 |
| Follow through | 3.5 | 1 | 7.4 | 4.7 | 108.0 |
| Barium enema | 4.7 | 1 | 7.4 | 4.7 | 108.0 |
| Myelogram | 4.8 | 1 | 12.3 | 7.2 | 179.6 |

The number of days in tables 4.12 and 4.13 is less because HSG procedures were conducted by two radiologists who were working together in the room at the same time. The dose recording of the first day of the data collection brought awareness on their radiation exposure. Therefore, for optimization purpose, RAD 2 and RAD 3 divided themselves in such a way that one conducts procedure while the second one observe from the console room daily.

According to table 4.11, the average number of procedures performed by RAD 1, RAD 2 and RAD 3 was found between 2 – 3 per day. In these cases only the double dosimetry method of estimation of the effective dose is considered for the discussion. The lowest dose recorded by RAD 1 were observed on day 6 with the corresponding values 0.7 μSv and 19 μSv for effective dose and eye lens dose. These dose were recorded performing two RUG procedures in 1.7 minutes. The highest doses were 6.1 μSv and 118.3 μSv

recorded for five procedures (3 RUG and 2 MCUG) performed in 5.3 minutes. The trend of this results shows that worker dose increases with the number of procedures and the fluoroscopy time. This assumption is not verified for RAD 2 and RAD 3 and RAD 4. The dose to RAD 2 performing four procedures in day 2 and day 4 were 12.4 μ Sv and 1.8 μ Sv respectively, for five procedures on day 3 and day 6 were 4.0 μ Sv and 6.6 μ Sv. This same scenario where observed with RAD 3 and RAD 4. Generally, it was observed that dose to RAD 2, RAD 3 and RAD 4 were not uniformly distributed in function of number of procedures performed or the screening time. This shows that the dose to the worker is influenced by many other factors related the worker.

Table 4.15 represents the monthly workload (in terms of time and number of procedures performed), the effective dose estimated by three (3) different methods and eye lens dose to radiologists.

Table 4. 15: Estimated monthly workload, effective dose and eye lens dose to the Radiologists.

| | Total Time (min) | N° of procedures | Single in E1 (mSv) | Single out E2 (mSv) | Double E3 (mSv) | E eye (mSv) |
|--------------|---------------------|---------------------|-----------------------|------------------------|--------------------|----------------|
| RAD 1 | 32.10 | 32 | 0.01 | 0.04 | 0.03 | 0.55 |
| RAD 2 | 36.30 | 69 | 0.02 | 0.04 | 0.03 | 0.57 |
| RAD 3 | 37.67 | 69 | 0.01 | 0.04 | 0.03 | 0.53 |
| RAD 4 | 30.90 | 8 | 0.02 | 0.23 | 0.14 | 3.39 |

Table 4.15 shows a great variation in the number of procedures performed by Radiologists: 32, 69, 69 and 8, but the screening time almost the same 32.10, 36.30,

37.70 and 30.90 minutes respectively. this imply that the screening time is not figured by the number of procedure, it depend on the type of procedure and the anatomy of the patient. RAD 4 has recorded the highest effective dose and eye lens dose (0.11 mSv and 3.39 mSv) even though having the smallest workload. This can be attributed to the poor application of protective measures and also the position occupied (very close to the patient and to the direct beam) when performing the procedure. But RAD 1, RAD 2 and RAD 3 recorded the same amount of effective dose and eye lens dose . This was predictable from the patient dose and fluoroscopy time analysis done in section 4.3.1. Where it was found that dose delivered to patients and fluoroscopy time were almost similar RUG, MCUG and HSG were in the same range. The result of the estimated effective dose using three differents methods agree with ICRP assumption saying that, “dose monitoring with one dosimeter placed inside lead apron underestimate the dose (ICRP, 2000). A dosimeter worn outside lead will overestimate the dose and the best way to monitor the workers conducting fluoroscopy procedures is the double dosimetry in case of hight radiation exposure.”

The monthly dose compared with ICRP recommendation (ICRP, 2007) is presented in figure 4.1.

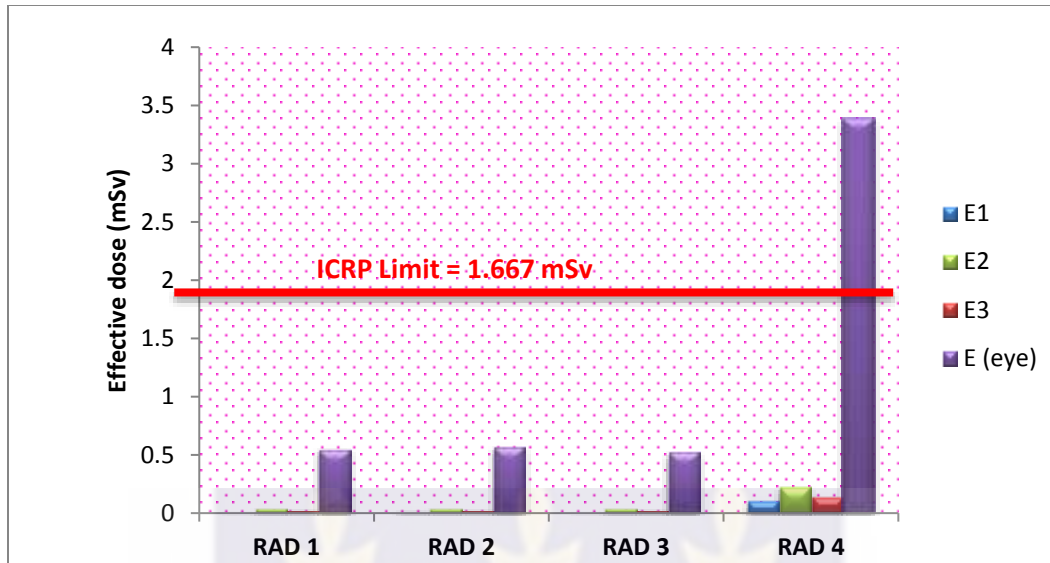


Figure 4.1: Estimated effective and eye lens dose compared with ICRP limit

Both effective dose and eye lens dose to RAD 1, 2 and 3 were found far below (42 times less for effective dose, 3 times less for eye lens) the limit regardless the method used for estimation. In the same line, effective dose to RAD 4 was below the limit (by a factor 12) but the dose to the lens of eye has double the limit. It has exceeded to the investigation level (2 mSv/ month) proposed by Duran et al (2013). An investigation should be carrying out to this particular worker to check the circumstances that lead to that high eye dose. The purpose of which is to keep the dose As Low As Reasonable Achievable (ALARA). Because of the proximity of Radiologists to the patient, for some procedures the hands of some radiologists were exposed to the direct beam. Therefore, are likely to received high radiation doses. The monitoring of Radiologists hands is required

4.4. Patients and Cardiologists Dose in Cathlab

Table 4.16 shows the number of procedures that have been carried out by Cardiologists in cathlab of KBTH during the period of data collection (two months). Figure 4.2 presents the frequencies of procedures in the laboratory.

Table 4. 16: Number of procedures performed by cardiologists during the period of data collection.

| Procedures | Abbreviations | N° cases |
|---------------------------------|---------------|-----------|
| Coronary Angiogram | CA | 30 |
| Right Heart Catheterization | RHC | 6 |
| Percutaneous Coronary Angiogram | PCI | 14 |
| TOTAL | | 50 |

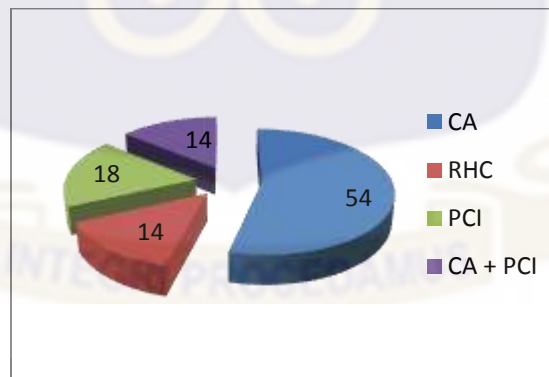


Figure 4.2: frequency of procedures in the cathlab

Coronary Angiogram is a diagnostic procedure and is the most performed in the cathlab. It is sometime associated with intervention procedures (PCI). RHC is a procedure used to

check heart pressure of patients and it is done only for few patients who are programmed for surgery.

4.4.1. Patient Dose and Fluoroscopy Time

The KAP and fluoroscopy time were recorded by means of integrated KAP meter. The median, range values for investigated procedure are presented in table 4.17.

Table 4.17: Median and range values of KAP and fluoroscopy time for each procedure performed in cathab.

| A | Procedures | KAP (Gy/cm ²) | | Time (min) | |
|---|------------|---------------------------|--------------|------------|-------------|
| | | Median | Range | Median | Range |
| | CA | 27.2 | 14.2 - 120.6 | 3.9 | 1.7 - 16.3 |
| | PCI | 112.5 | 60.0 - 117.2 | 26.9 | 13.5 - 43.0 |
| | CA + PCI | 134.8 | 42.0 - 237.0 | 19.9 | 9.7 - 37.5 |
| | RHC | 5.8 | 4.4 - 33.6 | 4.8 | 4.3 - 11.8 |

large variation of DAP and screening time among procedures are observed. KAP ranges from 4.4 Gy.cm² (Right heart catheterization) to 237.0 Gy.cm² (combined CA + PCI). Fluoroscopy time ranges from 1.7 minutes (CA) to 43 minutes (PCI). Significant variation was also observed for different types of procedures for example, for CA procedure the minimum and maximum values of DAP and fluoroscopy time are 14.2 Gy.cm², 1.7 minutes and 120.6 Gy.cm², 16.3 min respectively. This large variation is observed for other type of procedure. This could be attributed to the complexity of patient

anatomy, the technique of the doctor, the number of cine and the patient – tube distance and angulation used. Patients undergoing PCI and CA + PCI procedures are likely to receive the highest dose, median DAP are 11.47 Gy.cm² and 134.8 Gy.cm², median fluoroscopy time are 26.9 minutes and 19.9 minutes respectively.

4.4.2. Cardiologists Doses

Contrary to Radiologists to whom is allocated specific type of procedures, Cardiologists are performing every type of procedure depending on their availability when patients are ready. Every procedure is performed by two Cardiologists present near the patient. The range of dose per procedures for different type of procedure conducted by Cardiologists is given in table 4.18.

Table 4.18: Effective dose per procedure to Cardiologists

| | CA (μSv) | PCI (μSv) | RHC (μSv) |
|-----------------|-------------|------------|-----------|
| Card 1 | 0.3 – 2.1 | 1.8 – 6.9 | - |
| Card 2 | 0.15 – 21.1 | 1.2 – 57.6 | 2.3 – 2.5 |
| Card 3 | 0.85 – 15.9 | 0.9 – 6.4 | 0.1 – 1.9 |
| Card 4 | 0.05 – 5.7 | 0.8 – 2.5 | 0.3 – 2.8 |
| Combined | 0.05 – 21.1 | 0.8 – 57.6 | 0.1 – 2.8 |

As expected, owing to patient dose presented in section 4.4.1, the dose range for RHC procedures is very lower (minimum 0.1 μSv, Maximum 2.8 μSv) than the dose range for other procedures. Morrish and Goldstone in (2008) estimated the dose to Cardiologists and found a range of (0.02 – 30.2) μSv per procedure for CA examinations and (0.17 –

31.2) μSv per procedure for PCI. In the same line Fardid *et al* in (2013) found the dose range per procedure to cardiologists for CA (0.3 – 14.3) μSv and (1.3 – 27.5) μSv for PCI. In general, the dose range received by all Cardiologists per procedures was 0.05 μSv to 21.1 μSv which is comparable to the range value of (0.2 – 18.8) μSv and (0.02 – 38.0) μSv obtained by Padovani and Rodella in (2001), Kim *et al* in (2008) respectively. The wide range of dose for each Cardiologist is attributed to the position of the Cardiologist from the patient, whether the Cardiologist is acting as an assistant or principal operator and the protective equipment used.

The number of cases per type of procedure conducted by each Cardiologist is presented in figure 4.3.

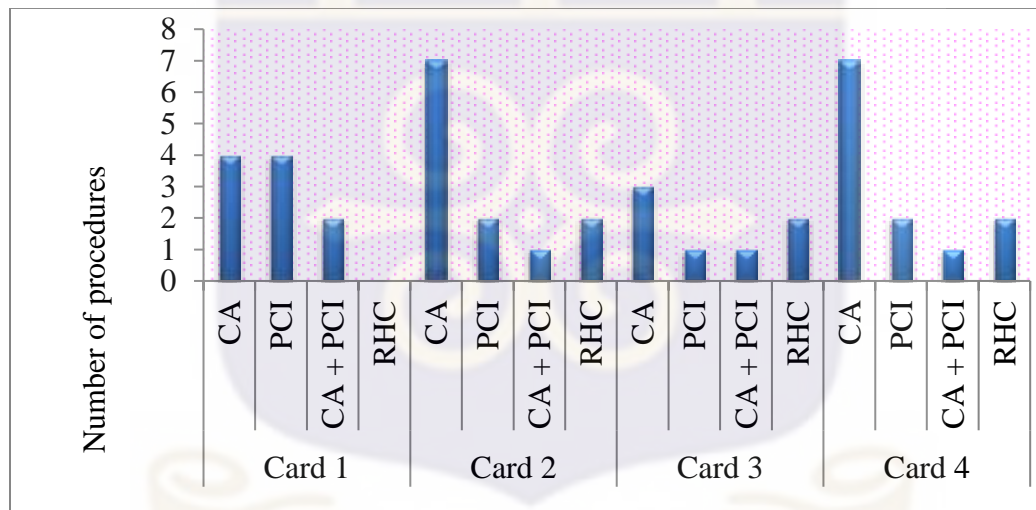


Figure 4. 3: Number of procedures conducted by Cardiologists Monthly

PCI and CA + PCI are mostly performed by Card 1 and CA by Card 2 and Card 3. Card 1 because of the expertise was always working as the principal operator and Card 4 as the assistant. From figure 4.3, Card 2 and Card 4 were the most frequent in the room with 12 procedures conducted by each, following by Card 1 with 10 procedures and lastly Card 3 with 7 procedures. To investigate the impact of each type of procedure on workers dose,

the dose received by Cardiologists for each type of procedure was estimated and is presented in figure 4.4 below.

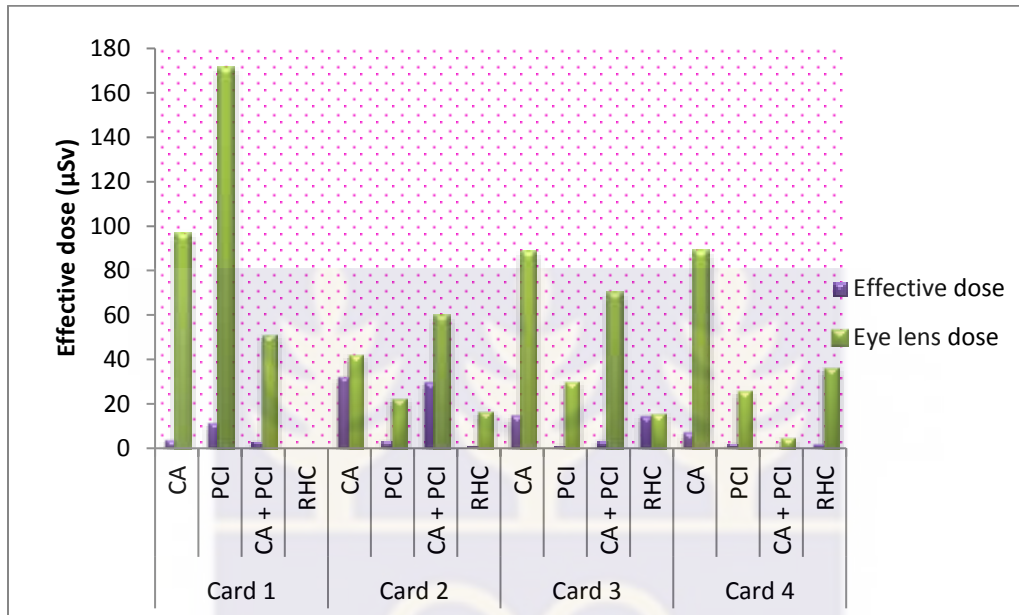


Figure 4.4: Estimated effective dose and eye lens dose to Cardiologists for different type of procedure

Figure 4.4 shows that the dose received by Card 4 for every type of procedure is far lower than the dose received by Card 2 even though they performed the same number of procedures. In the same perspective, the dose received by Card 1 conducting two procedures of CA +PCI, is lightly the same received by Card 2 conducting only one procedure. For the same number of RHC procedures conducted, it is observed that the dose received by Card 4 is almost two time the dose received by Card 3. Generally, all the great variation of dose to each Cardiologist per type of procedure owned to the fact that there is an inconsistency in the position occupied by different operators in the examination room. The most important observed fact is that most of RHC procedures were performed by Card 4 as principal operator and other were working as assistant. For

Card 1, PCI procedure is the most contributors in terms of dose (both effective and eye lens dose) because the complexity of the procedure and to the fact that, this particular Cardiologist always work as principal operator. For other Cardiologists, the CA procedures are the most contributors to the dose.

An average of 22 procedures was performed in the cathlab per month. The monthly workload (time and number of procedures) effective dose and eye lens dose to Cardiologists has been estimated and is presented in table 4.19.

Table 4.19: Monthly effective dose and eye lens to the Cardiologists

| | Fluoroscopy Time (min) | N° of procedures | Double E (mSv) | Eye lens Dose (µSv) |
|---------------|-----------------------------------|-----------------------------|---------------------------|--------------------------------|
| Card 1 | 177.0 | 10 | 0.02 | 0.30 |
| Card 2 | 129.0 | 12 | 0.07 | 0.25 |
| Card 3 | 77.1 | 7 | 0.02 | 0.20 |
| Card 4 | 109.2 | 12 | 0.01 | 0.15 |

Because of various types of procedures, some are lengthier and complex than other. An example is the comparison between the fluoroscopy time and the number of procedures performed by Card 1 (10 procedures, 177 minutes) and Card 4 (12 procedures, 109.15 minutes). Comparing the screening time to the effective dose, Card 1 has the highest workload, but effective dose is half of the dose to Card 2 who has a workload of 129 minutes and the same with Card 3 who has a workload of 77.1 minutes. But the eye dose to Card 1 were found to be the highest (0.3 mSv) among all the Cardiologists. Highest

eye dose and low effective dose show an adequate lead apron wear by Card 1. Card 2 record the highest effective dose because of his proximity to the patient during procedure. The lowest value of doses (0.01 μ Sv for effective dose and 0.15 μ Sv for eye lens) was recorded by Card 4 can due to the fact that mostly working as assistant operator.

In general, the low values obtained in this can be attributed to the small number of procedures conducted in this particular cathlab. The amount of radiation received by every worker depends also on the level of protective measure taken individually. The estimated annually dose was compared to the limit recommended by ICRP and is presented in figure 4.5 below (ICRP, 2007).

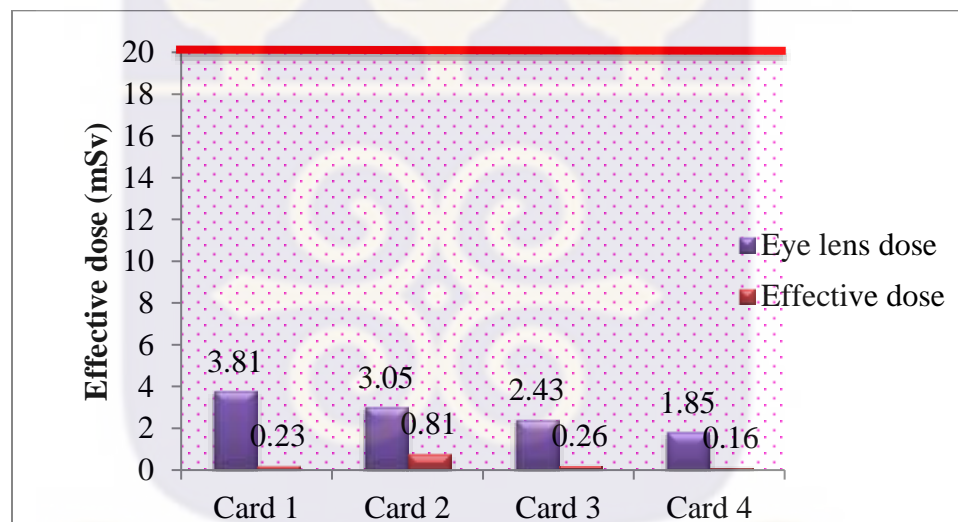


Figure 4.5: Estimated annual effective dose and eye lens dose compared to ICRP limits

The annually estimated effective dose and eye lens dose to the Cardiologists was found very low to ICRP recommended annual dose limit of 20 mSv (ICRP, 2007). These results are high compared the one obtained by Efstathopoulos *et al* (2003) who obtained a range of (0.04 – 0.03) mSv per year for principal operator considering a workload of 240 procedures. On the other hand, the estimated effective dose (0.16 – 0.81) mSv was

comparable to those published by UNSCEAR 2000 (0.4 mSv per year). The reported dose by Dendy (2008) was 2 – 4 mSv per year considering a workload of 1000 procedures. In 2009 Martin reviews the dose to cardiologists and found the dose per procedure between 0.2 and 4 μ Sv (few were found at 19 μ Sv) to the whole body and around 20 μ Sv for the lens of eye. He assumed that for 500 procedures each year, Cardiologists are likely to receive between 0.1 and 4 mSv per year. The projected number of procedures per Cardiologists in this study is averaged at 123 procedures per year, which is the quarter of what proposed by Martin. This can be the reason for low dose obtained in this study.

4.4.3. Risk Assessment to Cardiologists

The probability of cancer induced and heritable effect (or total detrimental risk) due to radiation exposure received by Cardiologists in this study was calculated using ICRP 2007 for individual risk coefficient and is presented in figure 4.6 below.

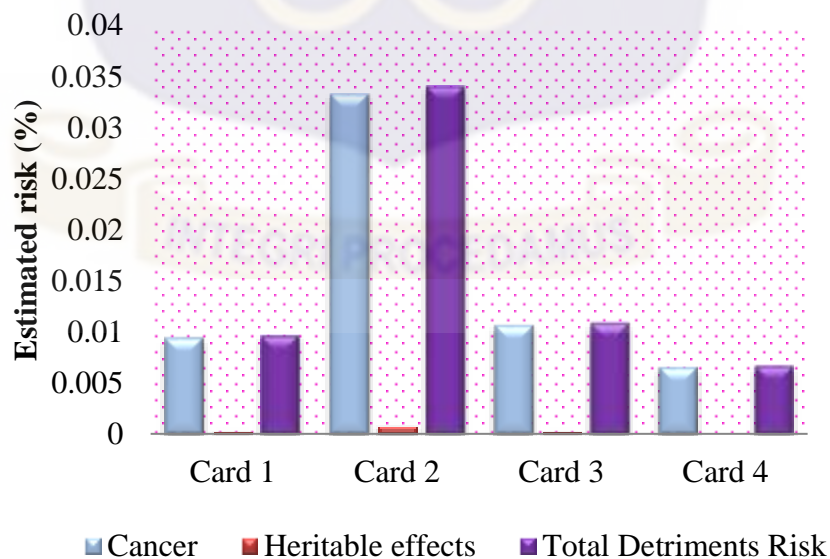


Figure 4.6: Estimated risk to Cardiologists

Due to the fact that the dose to Cardiologists was estimated for only one year, the risk estimation done in this study is very negligible. In addition, the workers are exposed to radiation during their life time.

In general, the estimated probability of health effect due to radiation to Cardiologists is not significant but should not be ignored. The LNT model assume that every amount of radiation (as small it can be) carries with it risk of cancer or heritable effect. Therefore, there is the need to enhance radiation protection actions in other to keep the dose As Low As Reasonably Achievable and reduce the likelihood of stochastic effects.

4.4.4. Relationship between Effective Dose and Patient Dose

The investigation into the relationship between patient dose (DAP) and Effective dose is given in figure 4.7.

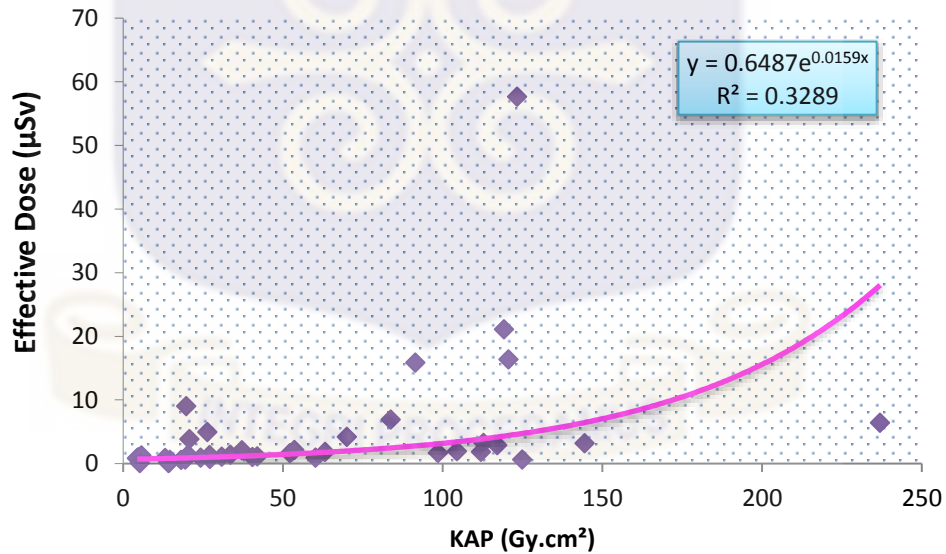


Figure 4.7: Relationship between Effective dose and patient dose

The plot of exponential relationship between KAP and effective dose gave the following equation 4.3:

$$Y (\text{effective dose}) = 0.6487 \times e^{0.0159 \times DAP} \quad \text{With } R^2 = 0.32 \quad (4.3)$$

Figure 4.7 shows that below KAP value of 150, the relationship between KAP and effective dose is likely to be linear. Looking at the previous equation 4.3, the value of R^2 shows that the relationship in general is weak, showing that the effective dose is influenced by other factors which have been stated in previous sections. The regression analysis of these two parameters gives a significant level ($P - \text{value} = 0.012 < 0.05$) meaning that this relationship is statistically significant, and the probability that it is related to chance is 0.012 which is very small. The linear relationship derived from the statistical analysis is following equation 4.4.

$$Y (\text{effective dose}) = 0.073 \times DAP + 0.2962 \quad \text{with } R^2 = 0.15. \quad (4.4)$$

The $p - \text{value}$ of the intercept is 0.89 which is greater than 0.05. This means that the intercept is more related to chance, so not reliable. This may be attributable to the non - uniform distribution of effective dose caused by the influence of another factor such as shielding, etc.

4.5. Investigation into other Factors affecting Workers Dose

A comparison of Cardiologists and Radiologists effective dose and eye lens dose against the workload presented in tables 4.15 and 4.19 in the previous sections shows that the workers are most exposed to radiation with over couch fluoroscopy tube than under couch tube. To support this statement, the Interventional Radiologist (IR) and the Assistant have been monitored during two procedures using the two configuration of the fluoroscopy tube and the results are given in table 4.20. The biliary drainage was

performed with over couch tube in radiology department and biliary stenting was performed with under couch tube at the cathlab.

Table 4.20: Dose records of interventional radiology procedures with overcouch and undercouch tube.

| Procedures | IR | | | | Assistant IR | |
|-------------------------|------------------------|------------|----------------------|----------------|----------------------|----------------|
| | DAP Gy.cm ² | Time (min) | Effective Dose (mSv) | Eye Dose (mSv) | Effective Dose (mSv) | Eye Dose (mSv) |
| Biliary drainage | 47.13 | 14.3 | 0.04 | 0.53 | 0.02 | 0.22 |
| Biliary stenting | 412.23 | 76.4 | 0.05 | 0.67 | 0.01 | 0.11 |

Biliary drainage procedure performed in the radiology department with fluoroscopy time of 14.3 minutes, the IR received 0.04 mSv and 0.53 mSv for effective dose and eye lens dose respectively. These values are lower (with a factor 1.25) than the dose received by the same IR (0.05 mSv and 0.67 mSv for effective dose and eye lens dose respectively) during 76.4 minutes (five times the screening time of biliary drainage). This high dose received in short time in the radiology department may be attributable to the geometry of the tube and the absence of additional shielding (lead glass and lead curtain) in radiology department. The assistant recorded half of the dose received in the radiology department owing to his position from the patient in the cathlab. The variation in staff effective doses for the same procedure can be attributed to the expertise of the worker and the protective garment used. The effect of the worker position in the room and the tube angulation during examination would be further explained in the following section.

4.6. Scattered Radiation in the Examination Room (Cathlab)

4.6.1. Modelling of the room

The X-ray source was modeled in a capsule made up of lead and placed under the patient couch. The modeled phantom was placed on the couch. It is shown in figure 4.8 below.

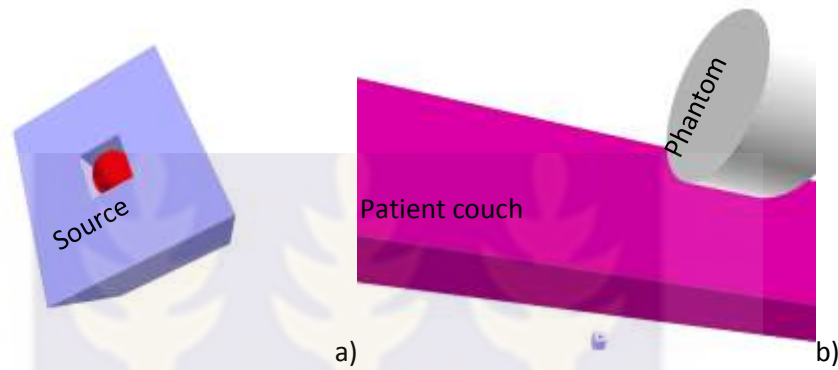


Figure 4.8. Source, patient table and phantom modeled with Simple Geo software

The room was modeled in respect with the measures taken at the real cathlab. The top and side views are presented in figure 4.9.

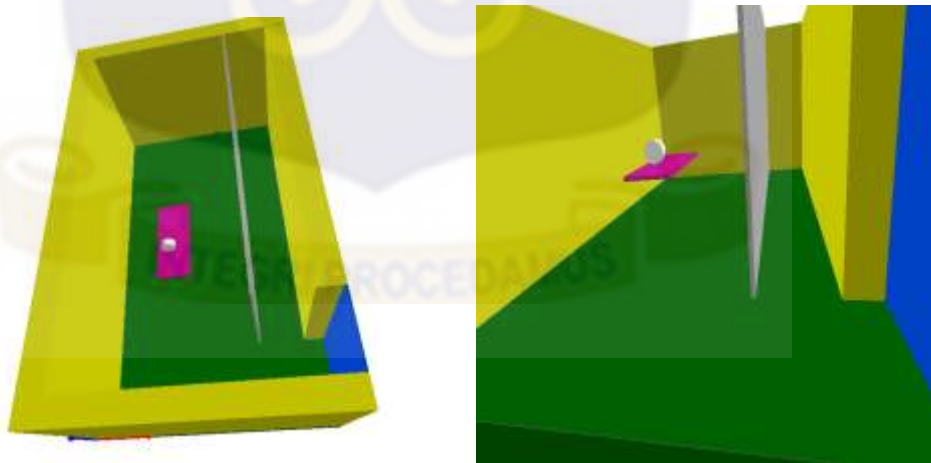


Figure 4. 9. Top and side view of the cathlab modeled with Simple Geo software

4.6.2. Distribution of Radiation in the Room for AP 0° of the Source

The file created by the Simple Geo was exported in MCNP 6 for simulation. Results were plotted using GnuPlot at different height from the floor of the source. The plots are presented in figures 4.10 and 4.11 below.

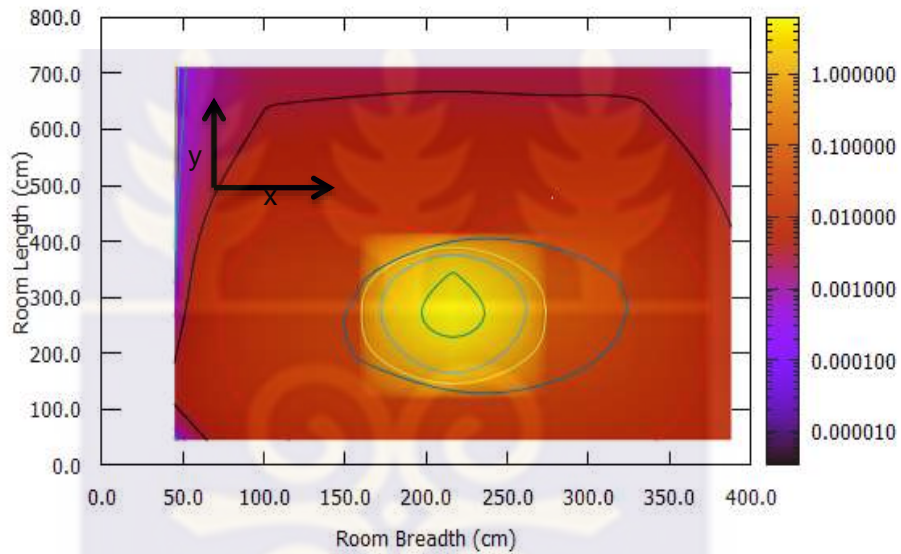


Figure 4.10: Dose distribution in the room at 85 cm from the floor

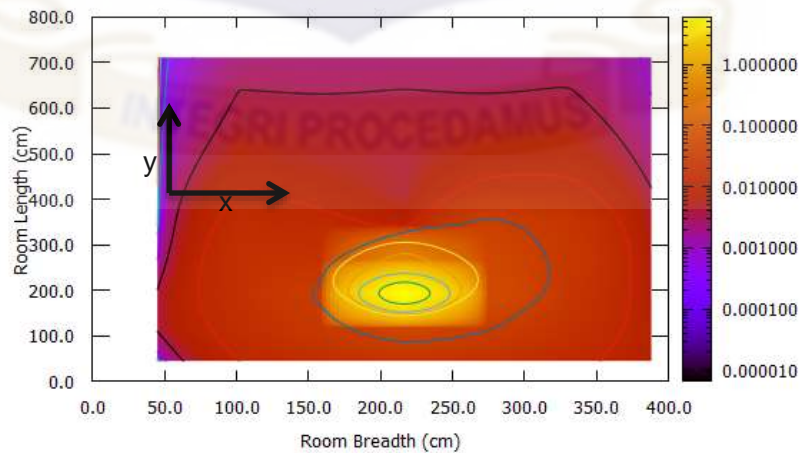


Figure 4.11: Dose distribution in the room at 107 cm from the floor

Figure 4.10 represents radiation distribution under the patient couch before any interaction, it shows that radiation is more concentrated around the patient couch and is spread all over the room. The safest place is negligible. This is the reason why a lead curtain must be always used to protect the operator's legs.

Figure 4.11 is the scattered radiation distribution at the level of the patient couch which is likely to be the trunk level of the operator. At this level the direct beam has interacted with the patient table and other materials on the patient couch. It can be observed that the safest place at the back of the room, behind the equipment is larger than the distribution at 85 cm. Also, the area of maximum radiation is smaller than the one at 85 cm, but it is around the table where the operator stays. It shows the importance of wearing lead apron properly. In both cases the nurses and any other person staying in the room are exposed to radiation. Therefore, they should also wear the protective garment. The head of the operator is the unshielded part of the body exposed to radiation. Figures 4.12 and 4.13 represent the distribution at the head level of the operator (150 cm and 171 cm)

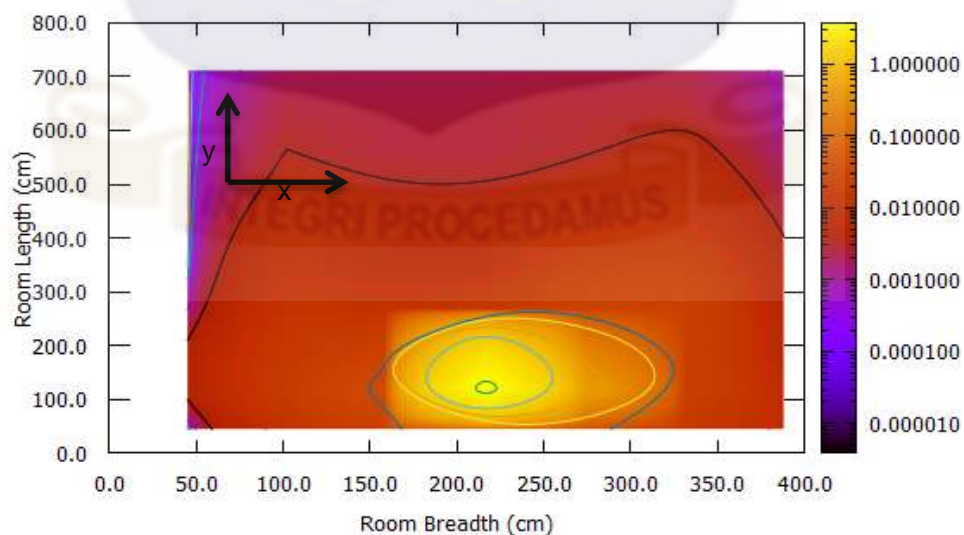


Figure 4.12: Dose distribution in the room at 150 cm from the floor

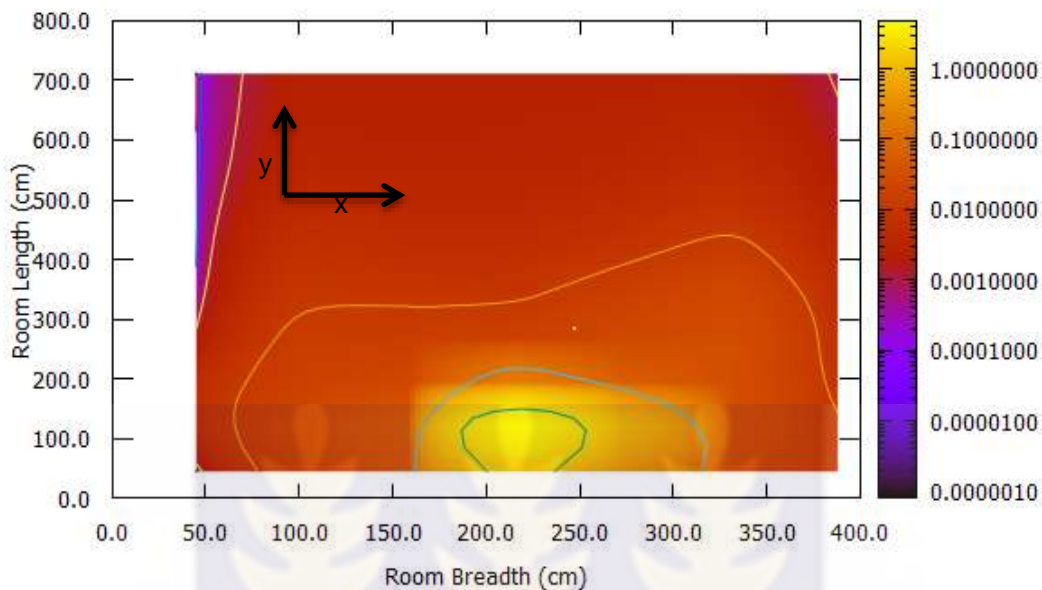


Figure 4.13: Dose distribution in the room at 171 cm from the floor

At 150 cm in figure 4.12, the safer place in the room is larger than at 171 cm on figure 4.13. The more it goes higher the more radiation is spread all over in the room and the maximum region is directed toward the entrance of the room where the nurse are likely to stay. Therefore, the taller nurses are likely to receive more radiation to the head (eye lens) than the operators staying near the patient. In general, everyone staying in the examination room is not safe. Thus, the safety measures must be applied by the operators and the nurses at the same level. The lead glass screen is one of the protective measures taken to reduce radiation to the head and hands of the operators.

4.6.3. Distribution of Radiation in the Room for LAO 30° and RAO 30° of the Source

The staff exposure is more influenced by the tube angulation used during procedures. Figures 4.14 and 4.15 represents the distribution at LAO 30° and RAO 30° of the source.

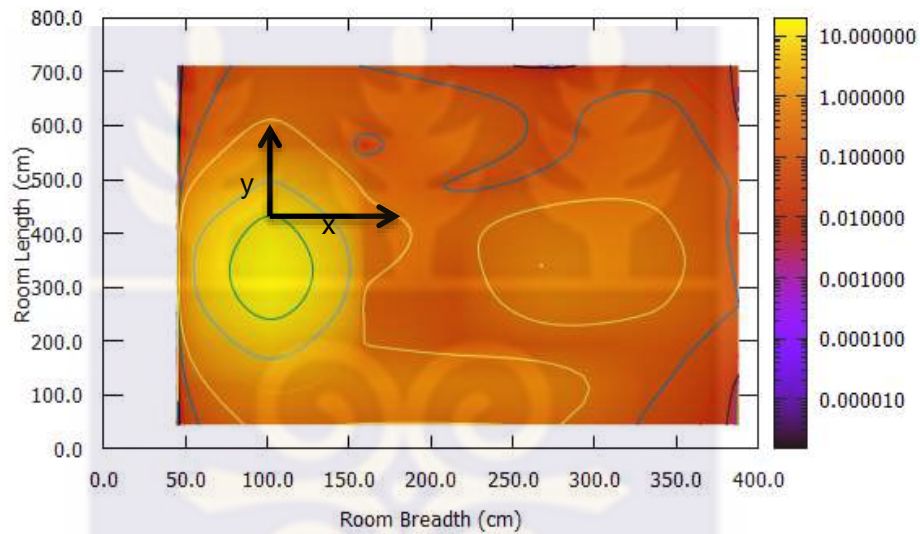


Figure 4.14: Dose distribution (LAO 30°) at 171 cm from the floor

Figure 4.15 shows that, there is no safe area in the room and the highest radiation is concentrated on the operator side. Therefore, the operators are more exposed to radiation when using the LAO anterior position of the tube.

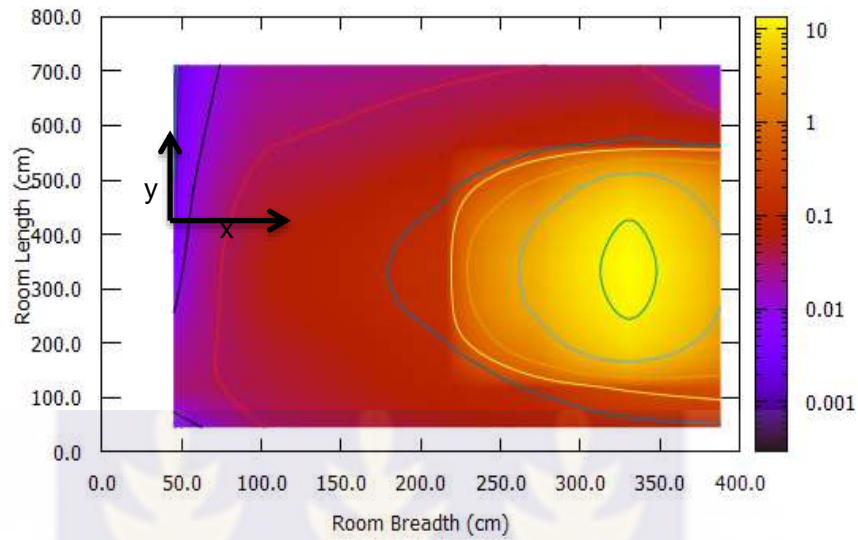


Figure 4.15: Dose distribution (RAO 30°) at 171 cm from the floor

For RAO 30° positions shown in figure 4.15, radiation is more concentrated at the opposite side of the operator.

4.6.4. Measured Values of the Scattered Radiation

The measured values of scattered radiation are presented in table 4.21 below. The operator's position is 180° at the right side of the patient.

Table 4.21: Measured values of scattered radiation

| | 0° (mSv/h) | 90° (mSv/h) | 180° (mSv/h) | 270° (mSv/h) |
|----------------|------------|-------------|--------------|--------------|
| AP 0° | 0.48 | 0.36 | 0.52 | 0.48 |
| RAO 30° | 1.08 | 0.60 | 0.54 | 1.56 |
| LAO 30° | 0.42 | 0.72 | 1.50 | 1.14 |

Table 4.21 shows that operators are more exposed to the radiation when the tube is at the position LAO 30°. These results agree with the computation in term of the most exposed and the safest area in the room.

Generally, every staff present in the room during the procedure is exposed to radiation especially to the head. Therefore, more protective actions (such as: additional shielding, stay at the safer position, etc) should be applied to keep the dose As Low As Reasonably Achievable.

4.7. Limitations of the study

The data was intended to be collected at least for two months in the Radiology Department but because of the delay in acquiring the ethical clearance and the dosimeters, the data was collected for only one month. An improvised water phantom was used for the scatter radiation measurement because of the unavailability of anthropomorphic phantom. The time allocated for the study was very limited to conduct a comprehensive risk assessment. Thus, a significant value of risk to the worker could be found in a study accounting for many years.

CHAPTER FIVE

5.0. Conclusion and Recommendations

Recent progresses in technology have resulted in the development and increased use of ionizing radiation for the purpose of diagnostic and treatment particularly in fluoroscopy. However, the awareness of the health effect of ionizing radiation should be considered and actions must be considered to reduce patient and staff dose. This chapter presents the general conclusion of this study and some recommendations emanating from the findings.

5.1. Conclusion

In this study, the effective dose and eye lens dose to four Radiologists using over couch fluoroscopy tube and four Cardiologists using under couch fluoroscopy tube was estimated using the double dosimetry method at KBTH and compared to other study using the same monitoring methods.

The effective dose and eye lens dose to the Radiologists were found lower than the limits recommended by ICRP except the eye lens dose to Rad 4 that was found higher by the factor 2. Therefore, monitoring of Radiologists eye lens for the identified specific procedures need more attention. The use of ceiling suspended glass and lead curtain would reduce the dose to the unshielded part such as eye, head, etc. therefore it is highly recommended for use in this department.

Dose to Cardiologists were comparable to other study, but were found far lower than ICRP dose limit (1.667 mSv). The effective dose and eye lens dose were not uniformly distributed. The interventional procedures were found to be lengthier, delivering

relatively high doses to patients. Therefore, the dose per procedure to the Interventional Radiologist was higher than other staff working in the same environment.

➤ The main factors that influence staff dose were observed to be: procedure types due to the access route used, geometry of the X-ray tube (staff are more exposed to radiation using over couch tube than under couch tube), position of the operator in the room during procedures, the tube angulation, and the experience of the staff. The most critical factor is the use of protective garment used by each operator. Occupational exposure is significantly influenced by patient exposure. Therefore, actions to reduce patient dose will also contribute to operator protection.

➤ The risk assessment shows that, no dose should be considered safe because any amount of radiation carries with it a risk.

➤ The Monte Carlo simulation of dose distribution in the room shows that, at certain height, the nurses are more exposed to the eye lens than the operators for AP0° and there is no safe position in the examination room. On other hand the operators are exposed to high radiation for LAO position of the tube and are safe for RAO position of the tube. Therefore, staffs are advised to wear protective equipment at all times during procedures. Optimization of protection (describe in the radiation safety programme proposed in appendix 6) should be considered by the operator to maximize patient safety keeping the dose ALARA without compromising the clinical outcome of the procedure.

5.2. Recommendations

Optimization in fluoroscopy is complex due to the complexity of procedures and the many technical factors that influence the dose. Therefore, training and quality assurance are indispensable. Because of the complexity of equipment used, quality control of the

many parameters involved is time consuming and a careful selection of the parameters to be controlled in constancy checks and frequency are essential part of the programme.

5.2.1. Establishment of a Radiation Safety Programme

The results of the investigation performed in both departments concerning radiation protection practice in section 4.1 shows insufficient radiation protection and safety measure considerations. The risk associated with low radiation exposure emphasizes the need for adequate measures to minimize patient and staff dose. This can be possible through the development and implementation of a radiation safety programme.

This study recommends the implementation of the proposed radiation safety program (Appendix 6). It is adopted from ICRP publication 139, Chamber et al (2011) and the purpose of this program is to increase the awareness of safety related to procedures involving radiation in order to provide to patient and all staff involved with radiation a safest environment possible for the best clinical outcomes.

5.2.2. Recommendation for Further Study

This study was limited by the duration, the type of dosimeter used and the collaboration with the administration and personnel. Therefore, the following are proposed for further study.

- This study was limited to occupational radiation exposure. However, high patient dose and long fluoroscopy time were recorded especially for interventional procedures. This shows the necessity to carry out a detailed and complete study on patient dose assessment in the catheterization laboratories in Ghana. In

addition, the growing number of procedures and the new operating cathlab created show the importance of establishing the dose reference level for the most performed cardiac catheterization procedures (CA and PCI) in Ghana.

- A study base measurements and Monte Carlo simulation aiming to develop an algorithm to accurately estimate effective dose to operators in Ghana using double dosimetry method.



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APPENDIX 1: Approval Letters



UNIVERSITY OF GHANA
ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES (ECBAS)

P. O. Box LG 1195, Legon, Accra, Ghana

Ref. No: ECBAS 013/17-18

21st February, 2018.

Miss Ruth Njantang
School of Nuclear and Allied Sciences
University of Ghana
Legon, Accra

Dear Miss Njantang,


ECBAS 013/17-18: ASSESSMENT OF RADIATION DOSES AND IMPLEMENTATION OF PROCEDURAL ROUTINE TO REDUCE OPERATOR EXPOSURE IN FLOUROSCOPY GUIDED PROCEDURE AT KORLE-BU TEACHING HOSPITAL

This is to inform you that the above reference study has been presented to the Ethics Committee for Basic and Applied Sciences for a full board review and the following actions taken subject to the conditions and explanation provided below:

Expiry Date: 20/02/19
On Agenda for: Initial Submission
Date of Submission: 09/11/2017
ECBAS Action: Approved
Reporting: Quarterly

Please accept my congratulations.

Yours sincerely,


Very Rev. Dr. Maxwell Aryee
Ag. ECBAS Chairperson



Tel: +233-207684121

Email: eoghartey@ug.edu.gh / ethicscbas@ug.edu.gh



In case of reply the number
And the date of this
Letter should be quoted

My Ref. No. *KBTH/MD/CS/18*
Your Ref. No.



KORLE BU TEACHING HOSPITAL
P. O. BOX KB 77,
KORLE BU, ACCRA.

Tel: +233 302 667759/673034-6
Fax: +233 302 667759
Email: info@kbth.gov.gh
pr@kbth.gov.gh
Website: www.kbth.gov.gh

5th March, 2018

RUTH NANA NJANTANG
SCHOOL OF NUCLEAR AND ALLIED SCIENCES
DEPT. OF MEDICAL PHYSICS
UNIVERSITY OF GHANA-ATOMIC

SCIENTIFIC AND TECHNICAL COMMITTEE APPROVAL
PROTOCOL IDENTIFICATION NUMBER: KBTH-STC 00093/2017

The Korle Bu Teaching Hospital Scientific and Technical Committee (KBTH-STC), on 5th March, 2018 approved your submitted study protocol.

TITLE OF PROTOCOL: "Assessment and optimization of occupational radiation doses in fluoroscopy guided procedure at Korle Bu Teaching Hospital"

PRINCIPAL INVESTIGATOR: Ruth Nana Njantang

This approval requires that you **forward your approved document to Korle Bu Teaching Hospital – Institutional Review Board (KBTH-IRB) for the ethical aspect of the proposal to be assessed before the project can be initiated.**

This STC approval is valid till 31st December, 2018

You may, however, request extension of the approval period, or renewal as the case may be, should the study extend beyond the stated period.

Upon completion, you are required to submit a final report on the study to the STC. This is to enable the STC ensure among others that, the project has been implemented as per the approved protocol.

You are also required to inform the KBTH-STC and Research Directorate of any publications that may emanate from the research findings.

Kindly note that, should the need arise, the KBTH-STC or IRB may institute appropriate measures to satisfy itself that study is being conducted according to the highest scientific and ethical standards.

Please note that any modification to the study protocol without Scientific Technical Committee (STC) approval renders this approval invalid.

Sincere regards,


Prof. Gabriel Obeng Adjei
Chairman, KBTH-STC

Cc: The Chairman, KBTH-IRB

In case of reply the number
And the date of this
Letter should be quoted

My Ref. No. KBTH/MD/G3/18
Your Ref. No.



KORLE BU TEACHING HOSPITAL
P. O. BOX KB 77,
KORLE BU, ACCRA.

Tel: +233 302 667759/673034-6
Fax: +233 302 667759
Email: info@kbth.gov.gh
pr@kbth.gov.gh
Website: www.kbth.gov.gh

26th April, 2018

RUTH NANA NJANTANG
DEPT. OF MEDICAL PHYSICS
SCHOOL OF NUCLEAR AND ALLIED SCIENCES
UNIVERSITY OF GHANA, LEGON

**ASSESSMENT AND OPTIMIZATION OF OCCUPATIONAL RADIATION DOSES IN
FLUOROSCOPY GUIDED PROCEDURE AT THE KORLE BU TEACHING HOSPITAL**

KBTH-IRB /00093/2017

Investigator: Ruth Nana Njantang

The Korle Bu Teaching Hospital Institutional Review Board (KBTH IRB) reviewed and granted approval to the study entitled "Assessment and optimization of occupational radiation doses in fluoroscopy guided procedure at the Korle Bu Teaching Hospital"

Please note that the Board requires you to submit a final review report on completion of this study to the KBTH-IRB.

Kindly, note that, any modification/amendment to the approved study protocol without approval from KBTH-IRB renders this certificate invalid.

Please report all serious adverse events related to this study to KBTH-IRB within seven days verbally and fourteen days in writing.

This IRB approval is valid till 30th July, 2019. You are to submit annual report for continuing review.

Sincere regards,

OKYERE BOATENG (MR)
CHAIR (KBTH-IRB)

Cc: The Chief Executive Officer
Korle Bu Teaching Hospital

The Director of Medical Affairs
Korle Bu Teaching Hospital

**MEDICAL DIRECTORATE
KORLE BU TEACHING HOSPITAL**

4th May, 2018

RUTH NANA NJANTANG
SCHOOL OF NUCLEAR AND ALLIED SCIENCES
UNIVERSITY OF GHANA, LEGON

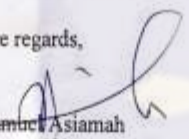
**INSTITUTIONAL APPROVAL: KORLE BU TEACHING HOSPITAL-SCIENTIFIC AND
TECHNICAL COMMITTEE/INSTITUTIONAL REVIEW BOARD (KBTH-
STC/IRB/00093/2017**

Following approval of your study entitled "Assessment and optimization of occupational radiation doses in fluoroscopy guided procedures at KBTH. A study at the Korle Bu Teaching Hospital" by the Korle Bu Teaching Hospital-Scientific and Technical Committee/Institutional Review Board. I am pleased to inform you that institutional approval has been granted for the conduct of your study in Korle Bu Teaching Hospital.

Please contact the Head of Department to discuss the commencement date of the study.

Please note that, this institutional approval is rendered invalid if the terms of the Institutional Reviewed Board/Scientific and Technical Committee approval are violated.

Sincere regards,


Dr. Samuel Asiamah
Director of Medical Affairs
For: Chief Executive Officer

INTEGRI PROCEDAMUS

APPENDIX 2: Data Collection Sheet

1. Patient's Data

| Procedures | DAP | Exposure time | Field size |
|------------|-----|---------------|------------|
| | | | |

2. Worker's Data

| Procedures | workers | Neck Hp(10) | Neck Hp(0.07) | Chest Hp(10) |
|------------|---------|-------------|---------------|--------------|
| | | | | |

3. Availability of Radiation Protection Equipment

- Identification of the X-ray unit (characteristic and parameters)
- Availability of personal protection
 - Lead apron
 - Thyroid collar
 - Gloves
 - Lead glasses
- Presence of additional protection

4. QC data Parameters

- Beam quality (HVL)
- Tube voltage, accuracy and reproducibility
- Tube current exposure time product (mAS)
- collimation
- Output consistency and linearity

5. Scatter dose measurement

| | 0° (µSv/h) | 90° (µSv/h) | 180° (µSv/h) | 270° (µSv/h) |
|----------------|------------|-------------|--------------|--------------|
| AP 0° | | | | |
| RAO 30° | | | | |
| LAO 30° | | | | |

APPENDIX 3: Questionnaire

PART A: General Information

1. Name of Department:
2. a. Responsibility of respondent:
 - b. For how long have you worked in radiology service?
3. Are you aware of radiation protection of workers?
4. What practices of staff protection do you know?
5. What practices does the department undertake?

PART B: Department Information

6. Information of fluoroscopy X-ray tube used:
7. Date of installation_____
8. a. Is there a Quality Assurance Program in the Department?
 - b. How frequent do you perform QC tests?
9. Is there a radiation safety committee or a radiation protection officer (RPO) in the department?
10. Is there any external expert who offers advice on radiation protection to the department?
12. Are areas in your facility designated as controlled and supervised areas?
13. Are there local rules in the department?
14. Are there radiation warning signs in the facility?
15. Are there warning lights at the entrance door to the X-ray room?

PART C: Personnel Protection

16. How many workers are in this department?

Radiologists: _____

Radiographers: _____

Medical Physicists _____

Nurses: _____

17. How many female workers are in the department?

18. Any rules for pregnant workers?

19. What protective wear are workers given?

- a. Lead aprons
- b. Lead gloves
- c. Gloves, lead glasses

20. Number of working days per week:

21. Average working hours (in the X-ray room) per day.

22. a. Are occupational doses monitored?

b. How are occupational doses monitored?

c. How frequent are they monitored?

23. How many workers have ever attended radiation protection training?


24. Are there staff exposure and health surveillance records?

25. a. Do you conduct radiation surveys or assessments around the working area?

b. How frequent?

28. Any emergency response mechanisms in place at the facility?

APPENDIX 4: Calibration Certificates

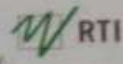


2021
D000001-1000

CALIBRATION CERTIFICATE

Calibration certificate issued by an accredited calibration laboratory.

AIR KERMA



www.rti.se

Page 1 of 2

| | | | |
|----------------------------|--|-----------------|--------------------|
| Certificate Number | 153F33222 | Customer | RTI Electronics AB |
| Serial number | CB2-19020088 | | |
| Date of calibration | 2015-03-11 | | |
| Object | kVp-, dose-, dose-rate- and time-meter | | |
| Manufacturer | RTI Electronics | | |
| Type | Pisante | | |
| Man. part number | 9629001 | | |
| Calibrated by | Mikael Björk, Calibration engineer | | |

Environment: All climatic conditions are within RTI's limits for a reliable calibration environment, i.e. 18-25 deg C, 90-110 kPa, and <70 % air humidity. For the solid-state detectors manufactured by RTI Electronics no temperature or pressure corrections of readings are required.

Room temperature 22.2 °C
Air pressure 102.3 kPa

Geometric arrangement: The detector was irradiated perpendicular to the entrance window. The reference point is 10,0 mm behind the cross on the surface of the detector. The depth is marked with a rim on the detector side.

Method: The method is described in the document MTB-020 Calibration method-Dose, by RTI Electronics AB.


Traceability: The calibration is performed by comparison against a reference dose detector. The reference detector is traceable through PTB (Germany) to national or international measurement standards.

Uncertainty: The expanded uncertainty for the calibration factor, N_K , at reference conditions when calibrating is ± 2.1 %. The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with EAL Publication EA-4/02.

Pass/Fail criteria: Pass/Fail criteria is set so that the objects specifications are fulfilled with a margin including the expanded uncertainty of the calibration. The criteria are specified in the method description referred to above.

Evaluation: A new calibration factor is derived every time the detector is recalibrated.

Authorized signature:



Mikael Björk
Calibration engineer

The calibration results refer exclusively to the object.
This calibration certificate may not be circulated other than in full.
Template version: 2014.5A

World Headquarters - Sweden

RTI Electronics
Fågelbergsgatan 8 C
SE - 431 37 Mölndal, Sweden

Phone: +46 31 746 36 00
Fax: +46 31 27 05 73
info@rti.se

www.rti.se
Momsregistreringsnummer: 556230246201
VAT Number: SE556230246201

A. Lenneman
Sveväg 104 - Svedala, 671 82, Skåne - Lundmark
Sweden - Lenneman
Tel: +46 40 52 02 719 - Fax: +46 40 52 02 719
www.rti.se

B. Theodorsson
21 Karlavägen, 401 30, Söderby - Theodorsson
Tel: +46 40 78 31 31 - Fax: +46 40 78 31 31
www.rti.se

C. Rönner
Rönner Office Park, Skövdeparken 100, Skövde
P.O. Box 10024 - 501 00, Skövde, Sweden
Tel: +46 31 734 34 31 - Fax: +46 31 734 34 31



CALIBRATION CERTIFICATE

Calibration certificate issued by an accredited calibration laboratory

TUBE VOLTAGE



Page 1 of 2

| | | | |
|----------------------------|--|-----------------|--------------------|
| Certificate number | 553428179 | Customer | RTI Electronics AB |
| Serial number | 582-1902085 | | |
| Date of calibration | 2019-03-11 | | |
| Object | XRF - Steel - stainless steel and iron metal | | |
| Manufacturer | RTI Electronics | | |
| Type | Piranha | | |
| Main part number | 9029501 | | |
| Calibrated by | Mikael Björk, Calibration engineer | | |

Environment: All climatic conditions are within RTI's limits for a reliable calibration environment, i.e. 16.25-26°C, 50-110 kPa, and $\pm 75\%$ air humidity.

| | |
|------------------------------|---|
| Geometric arrangement | The detector was installed perpendicular to the entrance window. The point of reference is 10.0 mm below the top window. |
| Method | The method is described in the document MTD-018 Calibration method Tube Piranha, by RTI Electronics AB. |
| Traceability | The calibration is performed by comparison against a reference high voltage divider system. The reference high voltage divider system is traceable through SP Technical Research Institute of Sweden to national or international measurement standards. |
| Uncertainty | The expanded uncertainty at reference conditions when calibrating is $\pm 0.55\%$. The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%. The standard uncertainty of measurement has been determined in accordance with EAL Publication EA-4/52. |
| Pass/Fail criteria | Pass/Fail criteria is set so that the objects specifications are fulfilled with a margin including the expanded uncertainty of the calibration. The criteria are specified in the method description referred to above. Pass/fail criteria for XRF calibrations of the Piranha is $\pm 1.5\%$. |
| Evaluations | The measured values are within the error limits specified by the manufacturer of the equipment under test. |

Authorized signature



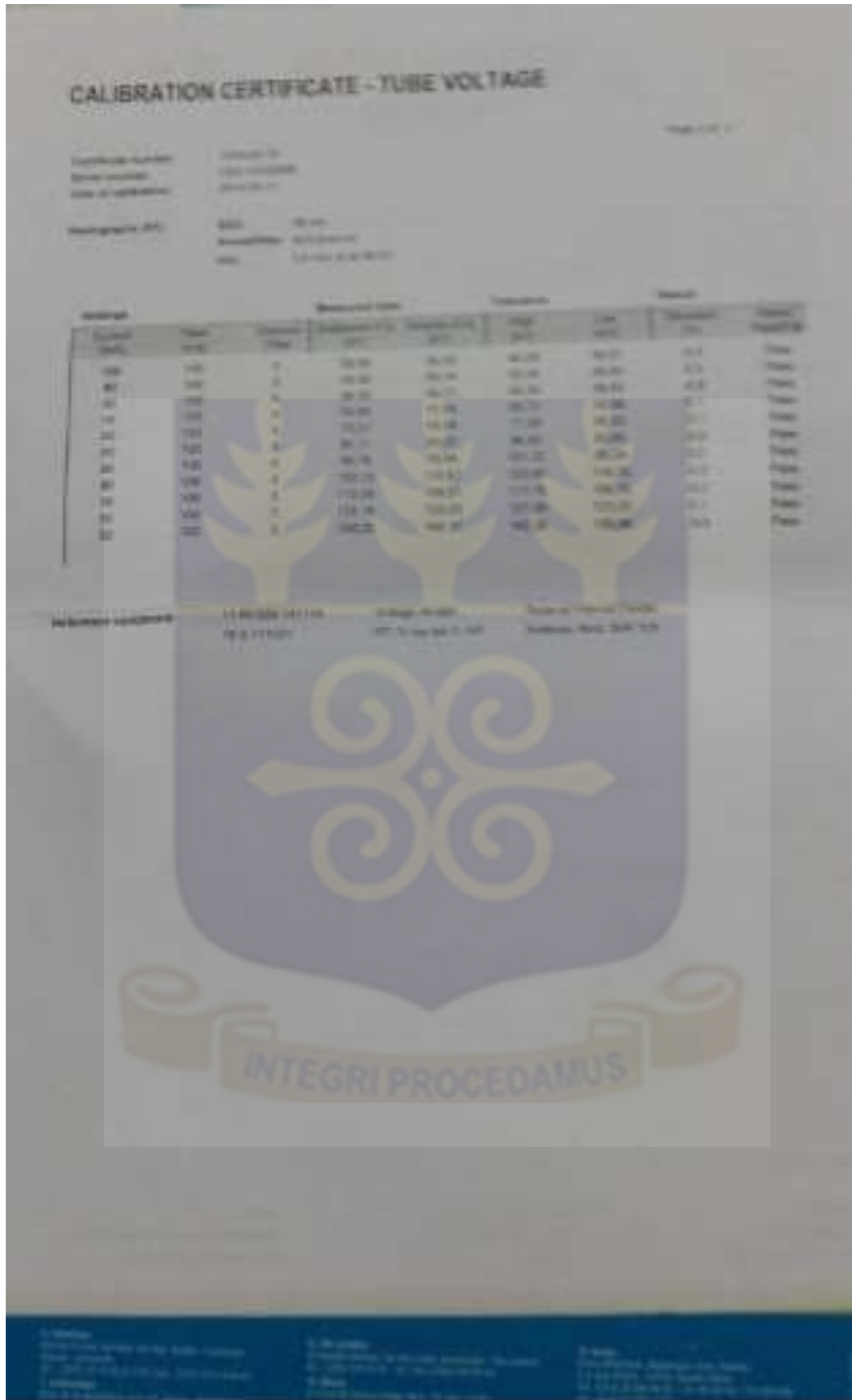
Mikael Björk
Calibration engineer

The calibration results refer exclusively to the object.
This calibration certificate may not be circulated other than in full.
Template version: 2014 5A.



| | | |
|--|---|---|
| <p style="font-size: x-small;">Wahlbergsgatan • Sweden</p> <p>RTI Electronics Fjällbergsgränd 8 C SE - 431 37 Mörndal, Sweden</p> | <p>Phone: +46 31 746 36 00 Fax: +46 33 27 25 73 info@rti.se</p> | <p>www.rti.se Skanningsträngsgatan 11C 4094201 WC Number: SE19420246201</p> |
|--|---|---|

| | | |
|--|---|--|
| <p>A. Sweden Svea Tekniska Institutet, AB 140, Svea - Gäddede SE - 221 22 Gäddede, Skåne, SE - 221 22 01 01 01 E: info@sti.se</p> | <p>B. The Netherlands STI Nederland, PO Box 1000, Terschelling, Texel NL - 1720 00 Terschelling, Texel Tel: +31 223 22 01 01</p> | <p>C. Italy STI Italia, Via Salaria, 1000, Roma, Italy IT - 00100 Roma, Italy Tel: +39 06 49 99 99 99</p> |
| <p>D. France STI France, 100 Avenue de la République, 93100 FR - 93100 La Plaine St Denis, France Tel: +33 1 48 38 38 38</p> | <p>E. Spain STI España, Calle de la Industria, 11, 28014 ES - 28014 Madrid, Spain Tel: +34 91 49 49 49</p> | <p>F. Germany STI Deutschland, Postfach 10 15 15, 10115 DE - 10115 Berlin, Germany Tel: +49 30 25 25 25</p> |



APPENDIX 5: Quality Control Results from Pirhana

Print date: 11/30/2017

Fluoroscopy

Test date: 11/30/2017

Measurements

| # | Tube voltage (KV) | Exposure time (ms) | Exposure (mGy) | Exposure rate (mGy/s) | HVL (mm Al) | Total filtr. (mm Al) | Exposure/frame (µGy/frame) | Frames/s (FPS) | Frames |
|----|-------------------|--------------------|----------------|-----------------------|-------------|----------------------|----------------------------|----------------|--------|
| 1 | 64.89 | 5.015 | 0.04022 | 5.690 | 3.21 | 4.9 | 40.22 | --- | 1 |
| 2 | 64.71 | 5.005 | 0.04918 | 7.517 | 3.17 | 4.8 | 49.18 | --- | 1 |
| 3 | 75.21 | 4.509 | 0.1085 | 15.39 | 3.75 | 5.0 | 108.5 | --- | 1 |
| 4 | 74.85 | 4.519 | 0.1078 | 16.40 | 3.73 | 5.0 | 107.8 | --- | 1 |
| 5 | 75.79 | 39.62 | 0.8409 | 19.70 | 3.83 | 5.1 | 840.9 | --- | 1 |
| 6 | 75.70 | 62.72 | 1.307 | 19.87 | 3.84 | 5.1 | 1307 | --- | 1 |
| 7 | 75.62 | 79.80 | 1.652 | 20.18 | 3.85 | 5.2 | 1652 | --- | 1 |
| 8 | 69.89 | 8.041 | 0.08343 | 8.277 | 4.30 | 7.7 | 83.43 | --- | 1 |
| 9 | 68.55 | 31.60 | 0.3634 | 10.80 | 4.16 | 7.5 | 363.4 | --- | 1 |
| 10 | 68.70 | 31.61 | 0.3637 | 10.49 | 4.14 | 7.4 | 363.7 | --- | 1 |
| 11 | 68.69 | 31.61 | 0.3653 | 10.53 | 4.14 | 7.4 | 365.3 | --- | 1 |

Test equipment used

Meter(s): Piranha S/N CB2-15020088
 Detector(s): MPD S/N MP2-15020080

Print date: 11/30/2017



kVp Accuracy Pulsed

Test date: 11/30/2017

Summary

Measurements

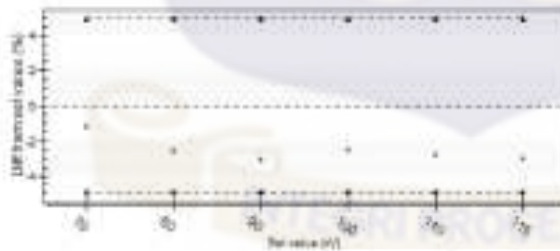
| # | Set kV (kV) | Tube voltage (kV) | kVp diff % | Exposure rate (mGy/s) | Frame/s (FPS) |
|---|-------------|-------------------|------------|-----------------------|---------------|
| 1 | 70 | 69.19 | -1.2 | 0.05504 | 15.1 |
| 2 | 80 | 87.25 | -3.1 | 0.0333 | 15.1 |
| 3 | 110 | 106.69 | -2.8 | 0.2428 | 15.2 |
| 4 | 115 | 111.55 | -3.0 | 0.2456 | 15.2 |
| 5 | 80 | 77.90 | -2.8 | 0.09427 | 15.1 |
| 6 | 100 | 97.46 | -2.5 | 0.1679 | 15.2 |

Analysis

Tube voltage accuracy

Result Pass

Maximum inaccuracy is -3.1 % at 80.00 kV (Limit: -5.0 % to 5.0 %)



Test equipment used

Meter(s) Plasma S/N CB3-15020088
 Detector(s) MPD S/N MPD-15020080

Fluoroscopy

Test date: 4/6/2018

Measurements

| # | Tube voltage (kV) | Exposure time (ms) | Exposure (mGy) | Exposure rate (mGy/s) | HVL (mm Al) | Total filtr. (mm Al) |
|---|-------------------|--------------------|----------------|-----------------------|-------------|----------------------|
| 1 | 77.38 | 270.0 | 0.4672 | 1.718 | 4.57 | 7.0 |
| 2 | 77.65 | 203.7 | 0.3735 | 1.815 | 4.56 | 6.9 |
| 3 | 77.55 | 270.0 | 0.4647 | 1.708 | 4.57 | 7.0 |
| 4 | 77.38 | 270.5 | 0.4696 | 1.720 | 4.57 | 7.0 |
| 5 | 77.49 | 270.5 | 0.4636 | 1.704 | 4.56 | 6.9 |

Test equipment used

Meter(s): Piranha S/N CB2-11020219
Detector(s): MPD S/N MP2-11020211



APPENDIX 6: Radiation Safety Programme for Occupationally Exposed Workers in Fluoroscopy Guided Procedure

1.0. Introduction

The improvement in technology results in the increase of number of procedure and number of facilities performing fluoroscopy procedures (for diagnostic and treatment). Thus, it is important that everyone involve with radiation receives radiation as low as possible. Therefore, it is a mandate for every x – ray department to have an implemented Radiation Safety Program for the safeguard of personnel and public from radiation exposure.

The following radiation safety program provides guidelines designed to ensure staff awareness on radiation health risk, also tools and knowledge for the best practice in radiation dose management. It will help the administration and staff to have knowledge and education in place to maintain safe radiation dose. Establishing this program should be a collective effort involving hospital administration and all staff involve with radiation. The target groups of this program are: the Medical Director of the hospital, the Director of NCTC, the Head of radiology department, Radiologists, Cardiologists, Nurses, Radiation Safety Officer (RSO), personnel dosimetry services, Radiographers, everyone interested with occupational exposure in fluoroscopy guided procedures.

2.0. Responsibilities

The Medical Director of the hospital has the overall responsibility for protection and safety of the member of staff involve with radiation. He must be part of the effective

implementation of radiation safety program and provides financial and adequate support to sustain a reasonable program while ensuring all regulatory requirements for patient and staff safety. He should appoint a Radiation Safety Officer who will work together with staff members and supervises all radiation safety issues in the department. Some of his responsibilities are:

- Authorize and register the safety program
- Review radiation safety policies and procedures
- Monitor and review equipment and radiation warning signs
- Evaluate individual monitoring and perform the risk assessment
- Survey all radiation areas for safety hazards
- Implements QA policies and procedures for X-ray equipment and personnel
- Review and submit report of RSP annually
- Education and training of all personnel involve with radiation
- Establish emergency plan and procedures

3.0. Individual Monitoring

Occupational dose monitoring is a critical element of radiation surveillance and is performed to verify compliance and optimize protection.

All staff whose work is associated with radiation must adequately and consistently wear their dosimeter. ICRP recommends the use of two dosimeters for operator in fluoroscopy. One dosimeter should be worn at waist level inside lead apron and one worn at neck level outside the apron. In case of the non-availability of two dosimeters for each operator, one should be worn outside the lead apron taking in account the unshielded part (head,

extremities). A separated dosimeter should be used for those personnel who work in more than one facility in order to identify the source of highest exposure. In case that the hands are exposed or work close to the direct beam, a wrist dosimeter should be considered for hand monitoring. The recommended dose limits are given in the following table.

Table 1: ICRP dose limits (ICRP, 2007)

| Effective Dose Limits | |
|--|--|
| 20 mSv per year averaged over 5 years (1.67 mSv / month) | |
| 50 mSv in a single year | |
| Equivalent Dose Limits | |
| Lens of the eye | 20 mSv per year averaged over 5 years (1.67 mSv / month) |
| | 50 mSv in a single year |
| Skin | 500 mSv per year averaged over 1 cm ² area of skin regardless of the area exposed |
| Extremities (hands and feet) | 500 mSv per year |

In case of high exposure an investigation should be carried out to know the elements causing the high exposure for optimization. The investigation level proposed by WHO is 0.6 mSv / month for effective dose.

Variety of dosimeters can be used in personnel dose monitoring include TLDs, film dosimeters, etc. but for the purpose of optimization and for detailed study on dose per procedures, APDs are highly recommended. The calibration of the APDs should include the radiation field representative of those encountered in fluoroscopy including tests in

pulsed mode with high dose rates. The quantities used in personnel dose monitoring are Hp (0.07), Hp (3) and Hp (10). In case that a dosimeter calibrated in term of Hp (3) is not available, Hp (0.07) can be used as an approximation of Hp (3) and Hp (10) can also be used only for photon spectrum with mean energy above 40 keV. The assessment of Scatter radiation field should be performed to verify the non – compliance with the procedure for wearing individual dosimeters by comparing with individual dosimeter readings.

Audits of occupational doses, investigation of abnormal exposure, recording, reporting results and corrective action if appropriate should also be considered.

4.0. Occupational Radiation Protection and Equipment

The action toward occupational protection is optimizing patient protection. Other means and actions include: the use of lead apron and thyroid collar, ceiling suspended screen shield and lead glasses, lead caps (if available), table suspended lead curtains and keeping distance from patient. A leaded drape and pad attached to the ceiling screen and be a mean of protection for operator hands for some specific procedures. The protective equipment should be characterized base on the radiation beam used to measure attenuation.

Protective apron should never be folded, to avoid crack in the lining and should be inspected using X-ray for any defects. The integrity of lead apron should be assessed annually. The hospital administration should ensure that adequate resources are available to purchase, test and replace them. The following figures are example of a well-equipped cathlab and operator.



Figure 1: Protective cathlab an equipped personnel

5.0. Education and Training

Every staff member should receive radiation dose management and adequate training in line with their responsibilities. The RSO should coordinate in collaboration with m staff member initial and periodic training of newly employed and operating workers.

Training program can be a series of online or standard classroom lectures focusing on:

- Physics of X-ray production and interaction
- Mode of operation of fluoroscopy machine
- Technical factors affecting image quality in fluoroscopy
- Dosimetry quantities and unit, biological effects of radiation
- Principle of radiation protection , local rules and requirements
- Techniques to minimize patient and staff dose

Because of the relationship between patient and operator protection in fluoroscopic procedures, the RSO, the personnel in charge of dosimetry services, clinical application specialist from suppliers and regulators also require training on clinical practice and specifications of X-ray equipment used in addition to general radiation protection. The

RSO or Medical Physicist should have the highest level of training because they are responsible to train other staff member.

6.0. Quality Assurance

A well establish QA program maintain best radiation protection practices and ensure adequate occupational exposure control. It should include, appropriate audit, to ensure that personnel adhere to procedures, especially related to wearing of dosimeter, protective devices and method to optimize occupational protection. It should establish the components of performance testing which are:

- Test to be performed, how often they are performed and acceptable limits for each test.
- A brief description of be used for testing and sample forms to be used.

Some X-ray tube and generator test that can be carried out are: filtration (HVL), focal spot size, kVp accuracy and reproducibility, mAs linearity, output waveforms, beam uniformity and alignment. The fluoroscopic system also requires visual and environmental inspection and performance testing.

7.0. Records for Quality Improvement

A quality program depends on good record keeping, therefore should be well documented, evaluated and updated. The following elements should be properly documented: Shielding calculations, inspections details and corrective actions.

Record on occupational dose consists of:

- The nature of the work
- Exposure from work for other facilities
- Outcomes of health surveillance
- Education and training of the workers
- Results of exposure monitoring and dose assessments including results of investigation of abnormal exposure values.

The member of staff should have access on the record of their own dose. Another important aspect of quality improvement is review which includes: policies and procedures, dose reports, inspections, repairs, audits, personnel consultations, unmet goals from previous years and non-compliance with maintenance.

8.0. Pregnant Workers

Ionizing radiation is one of the most agents that cause defects on embryo. Therefore the protection of pregnant workers needs a special consideration. Additional protection of the foetus should be considered immediately the pregnancy is known. On the other hand, pregnancy of a worker should not be a reason to perform procedures. A dosimeter placed inside the lead apron on the abdomen should be < 0.2 mSv/month.

9.0. Emergency Plan and Procedures

Emergency plan is an important component of a radiation safety program. It should help the personnel how to adequately identify, evacuate and react to emergency situations. The main goal is to protect the member of staff patient and public against potential accidents and it should include: plan of action, people involve in case of emergency (fire service,

police personnel, etc.) and placement of exit signs (such as illuminated warning signs for beam on/of, evacuation plan, location and use of fire extinguisher and pull station).



APPENDIX 7: Typical Monte Carlo Input File

```

c
c -----
c --- Cells -----
c -----
c
1 1 -2.3 -1 $ WALLB (CathLab_0 # WALLC)
2 1 -2.3 -2 $ WALLC (CathLab_0 # WALLC)
3 1 -2.3 -3 $ WALLA (CathLab_0 # WALLC)
4 1 -2.3 -4 $ WALLD (CathLab_0 # WALLC)
5 2 -7.874 -5 $ COUCH (CathLab_0 # WALLA)
6 1 -2.3 (-6) $ floor (CathLab_0 # WALLC)
7 1 -2.3 (-7) $ ceiling (CathLab_0 # WALLC)
8 3 -0.001205 (-8) $ Dr1Space (CathLab_0 # WALLD)
9 3 -0.001205 (-9 #10 #11 #12 #14 #5) $ XrSpace (CathLab_0 # WALLD)
10 3 -0.001205 -10 $ source (CathLab_0 # WALLD)
11 4 -11.35 (-11 (+12)) $ collimator (CathLab_0 # WALLB)
12 5 -1.19 -13 $ Phantom (CathLab_0 # COUCH)
13 4 -11.35 -14 $ Door (CathLab_0 # WALLB)
14 4 -11.35 -15 $ Divide (CathLab_0 # WALLB)
15 0 +17 $ Void
c -----
c --- Surfaces -----
c -----
1 rpp 0 45 0 830 0 300 $ WALLB (CathLab_0)
2 rpp 45 490 0 45 0 300 $ WALLC (CathLab_0)
3 rpp 445 490 165 785 0 300 $ WALLA (CathLab_0)

```

4 rpp 45 490 785 830 0 300 \$ WALLD (CathLab_0)
5 rpp 150 224 300 483 88.92 95 \$ COUCH (CathLab_0)
6 rpp 0 490 0 830 -50 0 \$ FLOOR1 (CathLab_0)
7 rpp 0 490 0 830 300 350 \$ Ceiling1 (CathLab_0)
8 rpp 445 485 45 165 0 300 \$ 1_1 (CathLab_0)
9 rpp 45 445 45 785 0 300 \$ 4_1 (CathLab_0)
10 s 200 370 30 0.01 \$ source (CathLab_0)
11 rpp 198 202 368 372 26.5 30.5 \$ 5_1 (CathLab_0)
12 rpp 199.92185 200.07815 369.094 370.094 29.594 30.5 \$ 5_2 (CathLab_0)
13 rcc 180 375 115 0 -15 9.184547654e-16 16 \$ Phantom (CathLab_0)
14 rpp 485 490 45 165 0 300 \$ Door (CathLab_0)
15 rpp 350 355 165 785 0 300 \$ Divide (CathLab_0)
17 rpp 0 490 0 830 -50 350 \$ box around building
c
c -----
c --- Mode -----
c -----
c
mode p
c
imp:p 1 13r 0
c
c -----
c --- Materials -----
c -----
c
m1 \$ Concrete (CathLab_0)

1000 -0.0221
6000 -0.002484
8000 -0.57493
11000 -0.015208
12000 -0.001266
13000 -0.019953
14000 -0.304628
19000 -0.010045
20000 -0.042951
26000 -0.006435

c

m2 \$ Steel (CathLab_0)

26000 +1

c

m3 \$ Air (ct_room_accra)

6000 -0.000124
7000 -0.755268
8000 -0.231781
18000 -0.012827

c

m4 \$ Lead (CT Gantry Accra)

82000 +1

c

m5 \$ PMMA (PMMA_0deg)

1000 -0.080541
6000 -0.599846
8000 -0.319613

```
c -----  
c --- Source -----  
c -----  
sdef par=p wgt=1 erg=D1 cel=10 x=200 y=370 z=30 rad=d2  
c -----  
c --- Source Distributions -----  
c -----  
sc1 Point Source Distribution: # head  
si1 H 0.0005 0.0010 0.0015 0.0020 0.0025  
0.0030 0.0035 0.0040 0.0045 0.0050  
0.0055 0.0060 0.0065 0.0070 0.0075  
0.0080 0.0085 0.0090 0.0095 0.0100  
0.0105 0.0110 0.0115 0.0120 0.0125  
0.0130 0.0135 0.0140 0.0145 0.0150  
0.0155 0.0160 0.0165 0.0170 0.0175  
0.0180 0.0185 0.0190 0.0195 0.0200  
0.0205 0.0210 0.0215 0.0220 0.0225  
0.0230 0.0235 0.0240 0.0245 0.0250  
0.0255 0.0260 0.0265 0.0270 0.0275  
0.0280 0.0285 0.0290 0.0295 0.0300  
0.0305 0.0310 0.0315 0.0320 0.0325  
0.0330 0.0335 0.0340 0.0345 0.0350  
0.0355 0.0360 0.0365 0.0370 0.0375  
0.0380 0.0385 0.0390 0.0395 0.0400  
0.0405 0.0410 0.0415 0.0420 0.0425  
0.0430 0.0435 0.0440 0.0445 0.0450  
0.0455 0.0460 0.0465 0.0470 0.0475
```

0.0480 0.0485 0.0490 0.0495 0.0500
 0.0505 0.0510 0.0515 0.0520 0.0525
 0.0530 0.0535 0.0540 0.0545 0.0550
 0.0555 0.0560 0.0565 0.0570 0.0575
 0.0580 0.0585 0.0590 0.0595 0.0600
 0.0605 0.0610 0.0615 0.0620 0.0625
 0.0630 0.0635 0.0640 0.0645 0.0650
 0.0655 0.0660 0.0665 0.0670 0.0675
 0.0680 0.0685 0.0690 0.0695 0.0700
 0.0705 0.0710 0.0715 0.0720 0.0725
 0.0730 0.0735 0.0740 0.0745 0.0750
 0.0755 0.0760 0.0765 0.0770 0.0775
 0.0780 0.0785 0.0790 0.0795 0.0800
 0.0805 0.0810 0.0815 0.0820 0.0825
 0.0830 0.0835 0.0840 0.0845 0.0850
 0.0855 0.0860 0.0865 0.0870 0.0875
 0.0880 0.0885 0.0890 0.0895 0.0900
 0.0905 0.0910 0.0915 0.0920 0.0925
 0.0930 0.0935 0.0940 0.0945 0.0950
 0.0955 0.0960 0.0965 0.0970 0.0975
 0.0980 0.0985 0.0990 0.0995 0.1000

| | | | | | |
|-------|-------------|-------------|-------------|-------------|-------------|
| sp1 D | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 2.56162E-08 |
| | 1.47956E-07 | 9.30689E-07 | 3.8289E-06 | 1.58249E-05 | 4.52987E-05 |
| | 0.000129956 | 0.000296961 | 0.000684586 | 0.001280192 | 0.002409286 |

0.003937936 0.006475987 0.009475574 0.013922641 0.01875253
0.025350137 0.032254988 0.041145166 0.049918449 0.060709287
0.071005743 0.083179034 0.094405477 0.10732336 0.119009585
0.132093088 0.14366044 0.1564176 0.166925401 0.178242096
0.188618685 0.19976588 0.208933707 0.218600813 0.226728106
0.235389214 0.242225636 0.249402647 0.254675851 0.260193097
0.264697476 0.269314622 0.27281472 0.276475796 0.279061166
0.28168915 0.283381798 0.285188167 0.286007238 0.286834259
0.286851368 0.286957138 0.286563567 0.286166816 0.28525584
0.284425957 0.282974298 0.28151876 0.279744891 0.278050208
0.276053731 0.274055474 0.271696464 0.269417085 0.266906257
0.264398863 0.261714146 0.259108486 0.256298346 0.253495901
0.250630553 0.24784261 0.244876198 0.241920344 0.238826665
0.235811724 0.232818918 0.22983756 0.226726516 0.223691478
0.220607656 0.217538782 0.214439377 0.211413434 0.208407462
0.2054158 0.202395708 0.199445324 0.196459959 0.193490113
0.190496098 0.187620892 0.184663766 0.181773169 0.178946809
0.653478728 0.17337035 0.17057293 1 0.165048115
0.162332933 0.159632506 0.156990148 0.154404205 0.151768844
0.14914792 0.146632385 0.144169386 0.141627201 0.139099073
0.136670483 0.134292075 0.131880402 0.404127408 0.127122886
0.124813486 0.122522786 0.191832891 0.117964345 0.104517736
0.102758686 0.1010011 0.099250447 0.097531022 0.095837356
0.09414369 0.092442074 0.090769842 0.089085717 0.087402609
0.085709961 0.084046951 0.082394245 0.080742748 0.07911949
0.077523644 0.075877362 0.074233242 0.072617807 0.07103023
0.069421982 0.067815452 0.066252425 0.064715793 0.063126988

0.061539926 0.059960026 0.058407913 0.056840066 0.055273821
0.053732228 0.052217221 0.050660936 0.049105942 0.04757569
0.046071705 0.044499297 0.042929211 0.041400911 0.039898764
0.03831653 0.036736457 0.035195094 0.033680265 0.032072774
0.030467407 0.028889796 0.027340291 0.025594236 0.023849142
0.022126359 0.020434493 0.018722052 0.017012053 0.015332774
0.013683909 0.010210753 0.006742792 0.003340765 0

si2 h 0 0.01 \$ inner and outer radii of sphere

sp2 d 0 1 \$ sampling range

c -----

c --- Mesh Tally \$ units (sieverts/h/source_particle) and MeV/cm3/particle-----

c -----

TMESH

RMESH1:p DOSE 30 1 2 1.0

CORA1 45 6i 445

CORB1 45 9i 785

CORC1 0 10i 300

ENDMD

c -----

c --- Control -----

c -----

stop nps=1900000000

prdmp j -60 1 1 100000

APPENDIX 8: Raw Data of the Simulation Results**1. Distribution for the tube position AP 0° at different height Z**

| x | y | Z | Value/Sv/h/particles | error |
|----------------|----------|----------|-----------------------------|--------------|
| 45 | 45 | 85.7143 | 9.61E-20 | 0.5383 |
| 102.143 | 45 | 85.7143 | 8.01E-17 | 0.0197 |
| 159.286 | 45 | 85.7143 | 1.14E-16 | 0.0158 |
| 216.429 | 45 | 85.7143 | 1.37E-16 | 0.0141 |
| 273.571 | 45 | 85.7143 | 1.25E-16 | 0.015 |
| 330.714 | 45 | 85.7143 | 9.45E-17 | 0.0177 |
| 387.857 | 45 | 85.7143 | 6.03E-17 | 0.0226 |
| 45 | 119 | 85.7143 | 3.27E-17 | 0.0309 |
| 102.143 | 119 | 85.7143 | 1.18E-16 | 0.0156 |
| 159.286 | 119 | 85.7143 | 1.91E-16 | 0.0121 |
| 216.429 | 119 | 85.7143 | 2.65E-16 | 0.0102 |
| 273.571 | 119 | 85.7143 | 2.27E-16 | 0.0111 |
| 330.714 | 119 | 85.7143 | 1.42E-16 | 0.0141 |
| 387.857 | 119 | 85.7143 | 6.25E-17 | 0.0201 |
| 45 | 193 | 85.7143 | 2.70E-17 | 0.029 |
| 102.143 | 193 | 85.7143 | 1.51E-16 | 0.014 |
| 159.286 | 193 | 85.7143 | 2.88E-16 | 0.01 |
| 216.429 | 193 | 85.7143 | 2.01E-14 | 0.001 |
| 273.571 | 193 | 85.7143 | 4.66E-16 | 0.0078 |
| 330.714 | 193 | 85.7143 | 1.85E-16 | 0.0125 |
| 387.857 | 193 | 85.7143 | 4.22E-17 | 0.0197 |
| 45 | 267 | 85.7143 | 8.64E-18 | 0.0512 |
| 102.143 | 267 | 85.7143 | 1.71E-16 | 0.0132 |
| 159.286 | 267 | 85.7143 | 3.12E-16 | 0.0093 |
| 216.429 | 267 | 85.7143 | 5.47E-14 | 0.0005 |
| 273.571 | 267 | 85.7143 | 7.69E-16 | 0.0056 |
| 330.714 | 267 | 85.7143 | 2.29E-16 | 0.0112 |
| 387.857 | 267 | 85.7143 | 4.43E-17 | 0.0188 |
| 45 | 341 | 85.7143 | 1.18E-18 | 0.1606 |
| 102.143 | 341 | 85.7143 | 1.54E-16 | 0.0142 |
| 159.286 | 341 | 85.7143 | 2.43E-16 | 0.0102 |
| 216.429 | 341 | 85.7143 | 2.93E-14 | 0.0003 |
| 273.571 | 341 | 85.7143 | 6.70E-16 | 0.0056 |
| 330.714 | 341 | 85.7143 | 2.09E-16 | 0.0116 |
| 387.857 | 341 | 85.7143 | 3.96E-17 | 0.0197 |
| 45 | 415 | 85.7143 | 6.48E-19 | 0.2517 |

| | | | | |
|----------------|-----|---------|----------|--------|
| 102.143 | 415 | 85.7143 | 1.03E-16 | 0.0179 |
| 159.286 | 415 | 85.7143 | 1.14E-16 | 0.016 |
| 216.429 | 415 | 85.7143 | 5.71E-17 | 0.0158 |
| 273.571 | 415 | 85.7143 | 1.78E-16 | 0.0129 |
| 330.714 | 415 | 85.7143 | 1.26E-16 | 0.016 |
| 387.857 | 415 | 85.7143 | 2.92E-17 | 0.0244 |
| 45 | 489 | 85.7143 | 3.32E-19 | 0.3781 |
| 102.143 | 489 | 85.7143 | 6.38E-17 | 0.0231 |
| 159.286 | 489 | 85.7143 | 6.91E-17 | 0.0221 |
| 216.429 | 489 | 85.7143 | 6.68E-17 | 0.0232 |
| 273.571 | 489 | 85.7143 | 7.76E-17 | 0.0209 |
| 330.714 | 489 | 85.7143 | 7.29E-17 | 0.0223 |
| 387.857 | 489 | 85.7143 | 1.94E-17 | 0.0331 |
| 45 | 563 | 85.7143 | 1.42E-19 | 0.4149 |
| 102.143 | 563 | 85.7143 | 3.93E-17 | 0.0303 |
| 159.286 | 563 | 85.7143 | 4.45E-17 | 0.0294 |
| 216.429 | 563 | 85.7143 | 4.68E-17 | 0.0285 |
| 273.571 | 563 | 85.7143 | 4.62E-17 | 0.0289 |
| 330.714 | 563 | 85.7143 | 4.59E-17 | 0.0291 |
| 387.857 | 563 | 85.7143 | 1.31E-17 | 0.042 |
| 45 | 637 | 85.7143 | 1.05E-19 | 0.4706 |
| 102.143 | 637 | 85.7143 | 2.80E-17 | 0.036 |
| 159.286 | 637 | 85.7143 | 2.95E-17 | 0.0367 |
| 216.429 | 637 | 85.7143 | 3.20E-17 | 0.0353 |
| 273.571 | 637 | 85.7143 | 2.99E-17 | 0.0361 |
| 330.714 | 637 | 85.7143 | 3.02E-17 | 0.0357 |
| 387.857 | 637 | 85.7143 | 8.94E-18 | 0.0543 |
| 45 | 711 | 85.7143 | 2.94E-20 | 0.5214 |
| 102.143 | 711 | 85.7143 | 2.14E-17 | 0.0432 |
| 159.286 | 711 | 85.7143 | 2.07E-17 | 0.0439 |
| 216.429 | 711 | 85.7143 | 2.21E-17 | 0.0422 |
| 273.571 | 711 | 85.7143 | 2.21E-17 | 0.0423 |
| 330.714 | 711 | 85.7143 | 2.35E-17 | 0.0423 |
| 387.857 | 711 | 85.7143 | 6.42E-18 | 0.0659 |
| 45 | 45 | 107.143 | 5.75E-20 | 0.4758 |
| 102.143 | 45 | 107.143 | 8.83E-17 | 0.0179 |
| 159.286 | 45 | 107.143 | 1.41E-16 | 0.0139 |
| 216.429 | 45 | 107.143 | 1.79E-16 | 0.0121 |
| 273.571 | 45 | 107.143 | 1.60E-16 | 0.0131 |
| 330.714 | 45 | 107.143 | 1.04E-16 | 0.0163 |
| 387.857 | 45 | 107.143 | 6.16E-17 | 0.0216 |
| 45 | 119 | 107.143 | 3.19E-17 | 0.0295 |
| 102.143 | 119 | 107.143 | 1.31E-16 | 0.0145 |

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|----------------|-----|---------|----------|--------|
| 159.286 | 119 | 107.143 | 2.32E-16 | 0.0109 |
| 216.429 | 119 | 107.143 | 4.41E-16 | 0.0072 |
| 273.571 | 119 | 107.143 | 2.96E-16 | 0.0094 |
| 330.714 | 119 | 107.143 | 1.59E-16 | 0.013 |
| 387.857 | 119 | 107.143 | 6.46E-17 | 0.0191 |
| 45 | 193 | 107.143 | 3.05E-17 | 0.0283 |
| 102.143 | 193 | 107.143 | 1.53E-16 | 0.0135 |
| 159.286 | 193 | 107.143 | 3.05E-16 | 0.0093 |
| 216.429 | 193 | 107.143 | 5.20E-14 | 0.0007 |
| 273.571 | 193 | 107.143 | 5.70E-16 | 0.0068 |
| 330.714 | 193 | 107.143 | 2.00E-16 | 0.0117 |
| 387.857 | 193 | 107.143 | 4.57E-17 | 0.019 |
| 45 | 267 | 107.143 | 8.82E-18 | 0.0516 |
| 102.143 | 267 | 107.143 | 1.55E-16 | 0.0133 |
| 159.286 | 267 | 107.143 | 1.71E-16 | 0.0122 |
| 216.429 | 267 | 107.143 | 3.79E-15 | 0.0015 |
| 273.571 | 267 | 107.143 | 4.59E-16 | 0.007 |
| 330.714 | 267 | 107.143 | 2.26E-16 | 0.0106 |
| 387.857 | 267 | 107.143 | 4.51E-17 | 0.0185 |
| 45 | 341 | 107.143 | 7.99E-19 | 0.1719 |
| 102.143 | 341 | 107.143 | 1.31E-16 | 0.0142 |
| 159.286 | 341 | 107.143 | 1.14E-16 | 0.0148 |
| 216.429 | 341 | 107.143 | 5.77E-17 | 0.022 |
| 273.571 | 341 | 107.143 | 3.55E-16 | 0.0076 |
| 330.714 | 341 | 107.143 | 1.98E-16 | 0.0113 |
| 387.857 | 341 | 107.143 | 3.95E-17 | 0.0202 |
| 45 | 415 | 107.143 | 3.22E-19 | 0.2776 |
| 102.143 | 415 | 107.143 | 9.16E-17 | 0.018 |
| 159.286 | 415 | 107.143 | 6.40E-17 | 0.0204 |
| 216.429 | 415 | 107.143 | 3.27E-17 | 0.0325 |
| 273.571 | 415 | 107.143 | 1.22E-16 | 0.0146 |
| 330.714 | 415 | 107.143 | 1.16E-16 | 0.0155 |
| 387.857 | 415 | 107.143 | 2.94E-17 | 0.025 |
| 45 | 489 | 107.143 | 1.27E-19 | 0.3534 |
| 102.143 | 489 | 107.143 | 5.49E-17 | 0.0241 |
| 159.286 | 489 | 107.143 | 4.22E-17 | 0.0266 |
| 216.429 | 489 | 107.143 | 3.35E-17 | 0.0293 |
| 273.571 | 489 | 107.143 | 6.07E-17 | 0.0224 |
| 330.714 | 489 | 107.143 | 6.76E-17 | 0.0221 |
| 387.857 | 489 | 107.143 | 1.80E-17 | 0.0344 |
| 45 | 563 | 107.143 | 2.18E-19 | 0.3932 |
| 102.143 | 563 | 107.143 | 3.65E-17 | 0.0309 |
| 159.286 | 563 | 107.143 | 3.53E-17 | 0.0308 |

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|----------------|-----|---------|----------|--------|
| 216.429 | 563 | 107.143 | 3.77E-17 | 0.0299 |
| 273.571 | 563 | 107.143 | 3.93E-17 | 0.0294 |
| 330.714 | 563 | 107.143 | 4.24E-17 | 0.0288 |
| 387.857 | 563 | 107.143 | 1.31E-17 | 0.0428 |
| 45 | 637 | 107.143 | 1.47E-19 | 0.5278 |
| 102.143 | 637 | 107.143 | 2.80E-17 | 0.0366 |
| 159.286 | 637 | 107.143 | 2.58E-17 | 0.0369 |
| 216.429 | 637 | 107.143 | 2.79E-17 | 0.0367 |
| 273.571 | 637 | 107.143 | 2.65E-17 | 0.0362 |
| 330.714 | 637 | 107.143 | 2.92E-17 | 0.0366 |
| 387.857 | 637 | 107.143 | 8.30E-18 | 0.0549 |
| 45 | 711 | 107.143 | 6.45E-20 | 0.4556 |
| 102.143 | 711 | 107.143 | 1.94E-17 | 0.0447 |
| 159.286 | 711 | 107.143 | 2.04E-17 | 0.0436 |
| 216.429 | 711 | 107.143 | 2.10E-17 | 0.0423 |
| 273.571 | 711 | 107.143 | 2.17E-17 | 0.0423 |
| 330.714 | 711 | 107.143 | 2.06E-17 | 0.0431 |
| 387.857 | 711 | 107.143 | 6.92E-18 | 0.0674 |
| 45 | 45 | 150 | 1.05E-19 | 0.5779 |
| 102.143 | 45 | 150 | 1.11E-16 | 0.0157 |
| 159.286 | 45 | 150 | 2.20E-16 | 0.0107 |
| 216.429 | 45 | 150 | 5.90E-16 | 0.0053 |
| 273.571 | 45 | 150 | 3.26E-16 | 0.0083 |
| 330.714 | 45 | 150 | 1.43E-16 | 0.0136 |
| 387.857 | 45 | 150 | 7.81E-17 | 0.0191 |
| 45 | 119 | 150 | 3.79E-17 | 0.0277 |
| 102.143 | 119 | 150 | 1.55E-16 | 0.0132 |
| 159.286 | 119 | 150 | 3.29E-16 | 0.0088 |
| 216.429 | 119 | 150 | 3.25E-14 | 0.0009 |
| 273.571 | 119 | 150 | 4.10E-15 | 0.0024 |
| 330.714 | 119 | 150 | 2.02E-16 | 0.0113 |
| 387.857 | 119 | 150 | 8.01E-17 | 0.0175 |
| 45 | 193 | 150 | 3.34E-17 | 0.0282 |
| 102.143 | 193 | 150 | 1.33E-16 | 0.0141 |
| 159.286 | 193 | 150 | 2.14E-16 | 0.0109 |
| 216.429 | 193 | 150 | 1.63E-14 | 0.0011 |
| 273.571 | 193 | 150 | 1.98E-15 | 0.0032 |
| 330.714 | 193 | 150 | 2.11E-16 | 0.0108 |
| 387.857 | 193 | 150 | 4.72E-17 | 0.0185 |
| 45 | 267 | 150 | 8.45E-18 | 0.0549 |
| 102.143 | 267 | 150 | 1.14E-16 | 0.0152 |
| 159.286 | 267 | 150 | 1.05E-16 | 0.0167 |
| 216.429 | 267 | 150 | 1.35E-16 | 0.0147 |

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|----------------|-----|-----|----------|--------|
| 273.571 | 267 | 150 | 2.29E-16 | 0.0101 |
| 330.714 | 267 | 150 | 2.14E-16 | 0.0103 |
| 387.857 | 267 | 150 | 4.61E-17 | 0.0188 |
| 45 | 341 | 150 | 9.36E-19 | 0.1539 |
| 102.143 | 341 | 150 | 8.66E-17 | 0.0176 |
| 159.286 | 341 | 150 | 6.27E-17 | 0.0222 |
| 216.429 | 341 | 150 | 6.37E-17 | 0.0229 |
| 273.571 | 341 | 150 | 1.62E-16 | 0.0118 |
| 330.714 | 341 | 150 | 1.73E-16 | 0.0113 |
| 387.857 | 341 | 150 | 3.70E-17 | 0.0212 |
| 45 | 415 | 150 | 2.19E-19 | 0.3128 |
| 102.143 | 415 | 150 | 5.92E-17 | 0.022 |
| 159.286 | 415 | 150 | 4.08E-17 | 0.0288 |
| 216.429 | 415 | 150 | 3.94E-17 | 0.0292 |
| 273.571 | 415 | 150 | 7.43E-17 | 0.019 |
| 330.714 | 415 | 150 | 9.93E-17 | 0.0158 |
| 387.857 | 415 | 150 | 2.61E-17 | 0.0263 |
| 45 | 489 | 150 | 2.04E-19 | 0.3276 |
| 102.143 | 489 | 150 | 3.79E-17 | 0.0283 |
| 159.286 | 489 | 150 | 2.77E-17 | 0.0346 |
| 216.429 | 489 | 150 | 2.79E-17 | 0.0352 |
| 273.571 | 489 | 150 | 3.85E-17 | 0.0279 |
| 330.714 | 489 | 150 | 5.44E-17 | 0.0225 |
| 387.857 | 489 | 150 | 1.68E-17 | 0.0351 |
| 45 | 563 | 150 | 4.65E-20 | 0.6719 |
| 102.143 | 563 | 150 | 2.74E-17 | 0.0351 |
| 159.286 | 563 | 150 | 2.09E-17 | 0.0396 |
| 216.429 | 563 | 150 | 2.13E-17 | 0.0389 |
| 273.571 | 563 | 150 | 2.60E-17 | 0.0349 |
| 330.714 | 563 | 150 | 3.66E-17 | 0.0294 |
| 387.857 | 563 | 150 | 1.07E-17 | 0.0453 |
| 45 | 637 | 150 | 3.37E-20 | 0.5678 |
| 102.143 | 637 | 150 | 2.10E-17 | 0.0399 |
| 159.286 | 637 | 150 | 2.00E-17 | 0.0406 |
| 216.429 | 637 | 150 | 2.13E-17 | 0.0397 |
| 273.571 | 637 | 150 | 2.39E-17 | 0.0387 |
| 330.714 | 637 | 150 | 2.49E-17 | 0.0367 |
| 387.857 | 637 | 150 | 7.85E-18 | 0.0551 |
| 45 | 711 | 150 | 7.89E-20 | 0.7259 |
| 102.143 | 711 | 150 | 1.58E-17 | 0.0463 |
| 159.286 | 711 | 150 | 1.70E-17 | 0.0459 |
| 216.429 | 711 | 150 | 1.79E-17 | 0.0448 |
| 273.571 | 711 | 150 | 1.99E-17 | 0.0429 |

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|----------------|-----|---------|----------|--------|
| 330.714 | 711 | 150 | 1.92E-17 | 0.0435 |
| 387.857 | 711 | 150 | 6.80E-18 | 0.0663 |
| 45 | 45 | 171.429 | 2.05E-20 | 0.5354 |
| 102.143 | 45 | 171.429 | 1.24E-16 | 0.0149 |
| 159.286 | 45 | 171.429 | 2.85E-16 | 0.0093 |
| 216.429 | 45 | 171.429 | 9.82E-15 | 0.0016 |
| 273.571 | 45 | 171.429 | 2.20E-15 | 0.0033 |
| 330.714 | 45 | 171.429 | 1.70E-16 | 0.0124 |
| 387.857 | 45 | 171.429 | 8.52E-17 | 0.0182 |
| 45 | 119 | 171.429 | 4.09E-17 | 0.0272 |
| 102.143 | 119 | 171.429 | 1.61E-16 | 0.013 |
| 159.286 | 119 | 171.429 | 3.59E-16 | 0.0084 |
| 216.429 | 119 | 171.429 | 3.46E-14 | 0.0008 |
| 273.571 | 119 | 171.429 | 6.72E-15 | 0.0019 |
| 330.714 | 119 | 171.429 | 2.18E-16 | 0.0109 |
| 387.857 | 119 | 171.429 | 8.18E-17 | 0.0176 |
| 45 | 193 | 171.429 | 3.59E-17 | 0.0288 |
| 102.143 | 193 | 171.429 | 1.18E-16 | 0.0154 |
| 159.286 | 193 | 171.429 | 1.61E-16 | 0.013 |
| 216.429 | 193 | 171.429 | 1.34E-15 | 0.0028 |
| 273.571 | 193 | 171.429 | 4.15E-16 | 0.0066 |
| 330.714 | 193 | 171.429 | 2.11E-16 | 0.0107 |
| 387.857 | 193 | 171.429 | 4.78E-17 | 0.0187 |
| 45 | 267 | 171.429 | 8.92E-18 | 0.0563 |
| 102.143 | 267 | 171.429 | 9.32E-17 | 0.0176 |
| 159.286 | 267 | 171.429 | 9.80E-17 | 0.0175 |
| 216.429 | 267 | 171.429 | 1.14E-16 | 0.016 |
| 273.571 | 267 | 171.429 | 1.62E-16 | 0.0125 |
| 330.714 | 267 | 171.429 | 2.11E-16 | 0.0103 |
| 387.857 | 267 | 171.429 | 4.40E-17 | 0.0191 |
| 45 | 341 | 171.429 | 1.19E-18 | 0.1427 |
| 102.143 | 341 | 171.429 | 6.75E-17 | 0.0207 |
| 159.286 | 341 | 171.429 | 6.03E-17 | 0.0234 |
| 216.429 | 341 | 171.429 | 6.17E-17 | 0.023 |
| 273.571 | 341 | 171.429 | 1.08E-16 | 0.0151 |
| 330.714 | 341 | 171.429 | 1.64E-16 | 0.0114 |
| 387.857 | 341 | 171.429 | 3.49E-17 | 0.0221 |
| 45 | 415 | 171.429 | 4.55E-19 | 0.268 |
| 102.143 | 415 | 171.429 | 4.77E-17 | 0.0251 |
| 159.286 | 415 | 171.429 | 3.78E-17 | 0.0295 |
| 216.429 | 415 | 171.429 | 3.79E-17 | 0.0299 |
| 273.571 | 415 | 171.429 | 5.59E-17 | 0.0224 |
| 330.714 | 415 | 171.429 | 9.36E-17 | 0.0161 |

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|----------------|-----|---------|----------|--------|
| 387.857 | 415 | 171.429 | 2.42E-17 | 0.0274 |
| 45 | 489 | 171.429 | 1.19E-19 | 0.328 |
| 102.143 | 489 | 171.429 | 3.16E-17 | 0.0319 |
| 159.286 | 489 | 171.429 | 2.63E-17 | 0.0356 |
| 216.429 | 489 | 171.429 | 2.58E-17 | 0.036 |
| 273.571 | 489 | 171.429 | 3.33E-17 | 0.0313 |
| 330.714 | 489 | 171.429 | 5.08E-17 | 0.0231 |
| 387.857 | 489 | 171.429 | 1.70E-17 | 0.0353 |
| 45 | 563 | 171.429 | 7.93E-20 | 0.4561 |
| 102.143 | 563 | 171.429 | 2.14E-17 | 0.0385 |
| 159.286 | 563 | 171.429 | 1.87E-17 | 0.0423 |
| 216.429 | 563 | 171.429 | 1.92E-17 | 0.0419 |
| 273.571 | 563 | 171.429 | 2.24E-17 | 0.0388 |
| 330.714 | 563 | 171.429 | 3.38E-17 | 0.0301 |
| 387.857 | 563 | 171.429 | 1.07E-17 | 0.0457 |
| 45 | 637 | 171.429 | 6.79E-20 | 0.6706 |
| 102.143 | 637 | 171.429 | 1.80E-17 | 0.0429 |
| 159.286 | 637 | 171.429 | 1.55E-17 | 0.0461 |
| 216.429 | 637 | 171.429 | 1.74E-17 | 0.0431 |
| 273.571 | 637 | 171.429 | 1.96E-17 | 0.0425 |
| 330.714 | 637 | 171.429 | 2.35E-17 | 0.038 |
| 387.857 | 637 | 171.429 | 8.14E-18 | 0.0562 |
| 45 | 711 | 171.429 | 5.62E-21 | 1 |
| 102.143 | 711 | 171.429 | 1.60E-17 | 0.0476 |
| 159.286 | 711 | 171.429 | 1.54E-17 | 0.0463 |
| 216.429 | 711 | 171.429 | 1.62E-17 | 0.0476 |
| 273.571 | 711 | 171.429 | 1.64E-17 | 0.0465 |
| 330.714 | 711 | 171.429 | 1.77E-17 | 0.0453 |
| 387.857 | 711 | 171.429 | 6.17E-18 | 0.0668 |

2. Distribution at the tube position LAO 30° at 163.6 cm from the floor

| X | Y | Value /Sv/h/particle |
|----------|----------|-----------------------------|
| 45 | 45 | 1.30E-25 |
| 102.143 | 45 | 3.90E-20 |
| 159.286 | 45 | 2.49E-20 |
| 216.429 | 45 | 2.56E-20 |
| 273.571 | 45 | 3.01E-20 |
| 330.714 | 45 | 6.84E-21 |
| 387.857 | 45 | 3.61E-24 |
| 45 | 119 | 1.40E-24 |
| 102.143 | 119 | 1.09E-19 |

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|---------|-----|----------|
| 159.286 | 119 | 7.24E-20 |
| 216.429 | 119 | 6.89E-20 |
| 273.571 | 119 | 6.06E-20 |
| 330.714 | 119 | 1.16E-20 |
| 387.857 | 119 | 8.20E-24 |
| 45 | 193 | 1.70E-24 |
| 102.143 | 193 | 4.67E-19 |
| 159.286 | 193 | 2.72E-20 |
| 216.429 | 193 | 8.99E-21 |
| 273.571 | 193 | 1.38E-20 |
| 330.714 | 193 | 1.39E-20 |
| 387.857 | 193 | 3.85E-21 |
| 45 | 267 | 1.20E-24 |
| 102.143 | 267 | 1.38E-18 |
| 159.286 | 267 | 1.70E-20 |
| 216.429 | 267 | 9.52E-21 |
| 273.571 | 267 | 5.70E-20 |
| 330.714 | 267 | 3.41E-20 |
| 387.857 | 267 | 8.93E-21 |
| 45 | 341 | 8.80E-24 |
| 102.143 | 341 | 1.77E-18 |
| 159.286 | 341 | 3.61E-20 |
| 216.429 | 341 | 1.24E-20 |
| 273.571 | 341 | 7.74E-20 |
| 330.714 | 341 | 4.93E-20 |
| 387.857 | 341 | 5.76E-21 |
| 45 | 415 | 3.70E-24 |
| 102.143 | 415 | 1.17E-18 |
| 159.286 | 415 | 3.46E-20 |
| 216.429 | 415 | 2.39E-20 |
| 273.571 | 415 | 4.81E-20 |
| 330.714 | 415 | 3.97E-20 |
| 387.857 | 415 | 2.13E-21 |
| 45 | 489 | 9.10E-24 |
| 102.143 | 489 | 3.25E-19 |
| 159.286 | 489 | 2.31E-20 |
| 216.429 | 489 | 4.54E-21 |
| 273.571 | 489 | 1.26E-20 |
| 330.714 | 489 | 2.44E-20 |
| 387.857 | 489 | 8.62E-21 |
| 45 | 563 | 7.80E-23 |
| 102.143 | 563 | 4.97E-20 |
| 159.286 | 563 | 8.70E-22 |

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|---------|-----|----------|
| 216.429 | 563 | 2.67E-20 |
| 273.571 | 563 | 4.49E-21 |
| 330.714 | 563 | 1.80E-20 |
| 387.857 | 563 | 2.24E-21 |
| 45 | 637 | 5.50E-24 |
| 102.143 | 637 | 2.72E-20 |
| 159.286 | 637 | 1.82E-20 |
| 216.429 | 637 | 1.49E-20 |
| 273.571 | 637 | 6.78E-21 |
| 330.714 | 637 | 1.55E-20 |
| 387.857 | 637 | 5.50E-24 |
| 45 | 711 | 4.30E-23 |
| 102.143 | 711 | 1.53E-20 |
| 159.286 | 711 | 8.44E-21 |
| 216.429 | 711 | 2.20E-21 |
| 273.571 | 711 | 1.50E-24 |
| 330.714 | 711 | 3.50E-21 |
| 387.857 | 711 | 6.29E-22 |

3. Distribution at the tube position RAO 30° at 171 cm from the floor

| X | Y | Value /Sv/h/particle |
|----------------|----------|-----------------------------|
| 45 | 45 | 2.55E-18 |
| 102.143 | 45 | 2.80E-16 |
| 159.286 | 45 | 3.60E-16 |
| 216.429 | 45 | 4.56E-16 |
| 273.571 | 45 | 5.69E-16 |
| 330.714 | 45 | 6.60E-16 |
| 387.857 | 45 | 5.69E-16 |
| 45 | 119 | 2.30E-16 |
| 102.143 | 119 | 3.53E-16 |
| 159.286 | 119 | 4.83E-16 |
| 216.429 | 119 | 6.73E-16 |
| 273.571 | 119 | 9.39E-16 |
| 330.714 | 119 | 3.11E-15 |
| 387.857 | 119 | 3.80E-15 |
| 45 | 193 | 1.51E-16 |
| 102.143 | 193 | 4.06E-16 |
| 159.286 | 193 | 5.42E-16 |
| 216.429 | 193 | 8.32E-16 |
| 273.571 | 193 | 1.59E-14 |

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|----------------|-----|----------|
| 330.714 | 193 | 6.78E-14 |
| 387.857 | 193 | 2.09E-14 |
| 45 | 267 | 7.77E-17 |
| 102.143 | 267 | 4.83E-16 |
| 159.286 | 267 | 6.65E-16 |
| 216.429 | 267 | 1.15E-15 |
| 273.571 | 267 | 3.21E-14 |
| 330.714 | 267 | 1.05E-13 |
| 387.857 | 267 | 2.80E-14 |
| 45 | 341 | 3.36E-17 |
| 102.143 | 341 | 5.09E-16 |
| 159.286 | 341 | 7.15E-16 |
| 216.429 | 341 | 1.29E-15 |
| 273.571 | 341 | 3.72E-14 |
| 330.714 | 341 | 1.18E-13 |
| 387.857 | 341 | 3.09E-14 |
| 45 | 415 | 1.57E-17 |
| 102.143 | 415 | 4.56E-16 |
| 159.286 | 415 | 6.22E-16 |
| 216.429 | 415 | 1.07E-15 |
| 273.571 | 415 | 2.97E-14 |
| 330.714 | 415 | 9.83E-14 |
| 387.857 | 415 | 2.66E-14 |
| 45 | 489 | 9.18E-18 |
| 102.143 | 489 | 3.68E-16 |
| 159.286 | 489 | 4.75E-16 |
| 216.429 | 489 | 7.19E-16 |
| 273.571 | 489 | 1.07E-14 |
| 330.714 | 489 | 5.14E-14 |
| 387.857 | 489 | 1.85E-14 |
| 45 | 563 | 5.10E-18 |
| 102.143 | 563 | 2.69E-16 |
| 159.286 | 563 | 3.38E-16 |
| 216.429 | 563 | 4.63E-16 |
| 273.571 | 563 | 6.92E-16 |
| 330.714 | 563 | 1.01E-15 |
| 387.857 | 563 | 8.36E-16 |
| 45 | 637 | 3.51E-18 |
| 102.143 | 637 | 2.10E-16 |
| 159.286 | 637 | 2.59E-16 |
| 216.429 | 637 | 3.31E-16 |
| 273.571 | 637 | 4.20E-16 |
| 330.714 | 637 | 4.91E-16 |

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|----------------|-----|----------|
| 387.857 | 637 | 1.60E-16 |
| 45 | 711 | 2.60E-18 |
| 102.143 | 711 | 1.70E-16 |
| 159.286 | 711 | 2.03E-16 |
| 216.429 | 711 | 2.39E-16 |
| 273.571 | 711 | 2.75E-16 |
| 330.714 | 711 | 2.99E-16 |
| 387.857 | 711 | 9.56E-17 |

