Hand-foot-clothes contamination in nuclear medicine: Monitoring of staff at Charlotte Maxeke Johannesburg Academic Hospital (CMJAH)

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Declaration

I, Phumlani Sithole, declare that this thesis is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

August 23, 2021

Abstract

Aim: This study seeks to assess contamination due to emitting radionuclides on hands, feet and clothing of staff in the nuclear medicine department. To achieve our aim, we measured the radionuclide contamination level of each staff member and compared the level of contamination among different staff categories (doctors, radiographers, nurses, general workers and students). We also determined the area that contributed to high contamination.

Methods: The study was conducted at Charlotte Maxeke Johannesburg Academic Hospital (CMJAH) for three months. We used a hand-foot-clothes contamination monitor (Mod CMS60DXD) to measure the level of radioactive contamination. Twelve doctors, fourteen radiographers, five students, four nurses, one medical physicist, one administrator, one secretary and two cleaners were enrolled in the study. The radioactive contamination was measured on the hands, feet and clothing of each participant. The measurements were taken in the morning, at lunchtime and just before leaving duty after work. Ethical permission for the study was received from the Human Research Ethics Committee (Human) of the University of the Witwatersrand (Clearance Certificate No. M170203).

Results: The detected radioactive contamination frequency was within the derived limit for surface contamination in 93% of left hands, 92% of right hands, 92% of left feet, 93% of right feet and 88% of clothing. Radiographers and students were most exposed to contamination outside the allowed limit. Contamination was not significant at the beginning of the day but increased with time and was mainly detected at lunchtime and before leaving work. Hot laboratory and gamma camera imaging rooms had the highest detected contamination. The primary source of contamination was ^{99m}Tc radionuclide compared to ^{18}F and ^{123}I radionuclides.

Conclusion: The results indicate that there is radioactive contamination in the Nuclear Medicine Department at CMJAH. Although the measured radioactive contamination was within the derived limit for surface contamination in the vast majority of participants, it remains vital to introduce mechanisms that will minimise staff exposure to radioactive contamination.

Dedication

This work is dedicated to my family, especially to my Mother, and to the Nuclear Medicine Department at CMJAH.

List of Abbreviations and Terminology

^{18}F-FDG	^{18}F-Fluoro-Deoxy-Glucose
ALARA	As Low As Reasonably Achievable
Bq/cm^2	Becquerel per Centimetre square
CaF2:Mn	Manganese-activated calcium fluoride
CMJAH	Charlotte Maxeke Johannesburg Academic Hospital
CT	Computed Tomography
DEXA	Dual-energy X-ray absorptiometry
DNA	Deoxyribonucleic acid
DNM	Department of Nuclear Medicine
AED	Annual Effective Dose
GA	General Assistants
GM	detector Geiger Müller detector
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units
IAEA	International Atomic Energy Agency
IQ	Interquartile
LiF	Lithium fluoride
NECSA	South African Nuclear Energy Corporation
NM	Nuclear medicine

NMD	Nuclear Medicine Department
PET	Positron Emission Tomography
PMT	Photomultiplier tube
RPO	Radiation Protection Officer
SABS	South African Bureau of Standards
STP	Standard Temperature and Pressure
TLD	Thermoluminescent Dosimeter
V/Q	Ventilation/perfusion

Acknowledgements

I would like to thank

- God, who is the source of life, good and everything begins with him; in his absence, everything stops. I quote, "if worry is the diagnosis, this is God's prescription. 1 Peter 5:7 (JBP) you can throw the whole weight of your anxieties upon him, for you are his personal concern."
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Chapter 1

Introduction

1.1 General introduction

Nuclear medicine (NM) is a section of medicine that uses radionuclides to diagnose and treat disease. These radionuclides are unsealed radioactive sources with unstable nuclei. The unstable nuclei decay to stable nuclei by emitting gamma rays, beta particles or both [1]. During nuclei decay, staff and members of the public may receive a radiation dose by both external and internal exposure pathways. Any personnel who work with unsealed radioactive material in Nuclear Medicine Department (NMD) may be subject to potential contamination if necessary safety procedures are not adhered to during normal operations [1, 2].

Internal exposure occurs by internal contamination, which occurs when radiopharmaceuticals are inhaled, ingested or absorbed through an opening in the skin. External exposure results from external contamination of the surface, hands, clothing and feet, or radioactive emission from the patients. External exposure from the radioactive patient, point source and surface contamination can be minimised by considering time, distance and shielding. When spent time is reduced to the vicinity of the radioactive source or contamination, the exposure to staff is reduced. The longer the time spent, the higher the radiation dose received by staff. Maintaining a larger distance reduces the exposure rate emitted from the radioactive patient, point source or contaminated surface. Shielding reduces exposure when high density and thickness materials such as concrete or lead are used as a barrier to radiation [2].

A good safety standard of practice in a NMD is required to control contamination arising from working with unsealed radioactive sources on any given day. Hands play a big role in causing internal contamination because they are used to hold food and clothes. Feet do not contribute directly to internal contamination but play a crucial role in transferring contamination from one place to another. Clothing also plays a role in transferring contamination from one person to another by physical contact and touching [3].

A hand-foot-clothes contamination monitor must be used to measure whole-body contamination. A hand-foot-clothes contamination monitor is an instrument that provides measures of radioactive contamination on each hand, the bottom of both feet and on the clothing [4, 5].

The most commonly used radionuclides in NM are Technetium-99m (^{99m}Tc), Fluorine-18 (^{18}F) and Iodine-131 (^{131}I). Their applications are continuously increasing for diagnostic and therapeutic procedures in most NM facilities worldwide. This has resulted in an increased benefit to patients; however, it is associated with a risk of radiation contamination and direct or indirect staff exposure [6]. It, therefore, becomes important to make the staff aware of the radioactive contamination they may receive and radiation doses they could be exposed to while working with these radionuclides [7]. Radionuclides with a high specific gamma-ray constant and penetrating factor such as ^{18}F with 511-keV photons result in higher ionising radiation exposure to personnel if not handled carefully; hence radionuclide contamination must be monitored [7, 8]. Radiation safety or contamination issues in the NMD have to be addressed adequately to lower the risk of occupational exposure hazards.

The staff working with radiation are monitored for their effective whole-body doses using Thermoluminescent Dosimeter (TLD) badges, and pregnant staff have additional audible dosimeters used for monitoring radiation exposure [6]. Although this is a good way to monitor exposure, reading is only done monthly and may not alert to the magnitude of daily contamination. The measurement of radioactive contamination to hands, feet and clothes of staff involved in handling radioactivity not only specifies the level of radiation safety standards maintained at a given centre but may also act as a guide for safe work practice. However, the contamination of hands, feet and clothes may increase the recommended effective dose limits for the radiation personnel. Hence, the International Commission on Radiological Protection (ICRP) recommends a

protection system to cover all possible exposure situations. Also, it recommended the annual effective dose limit for radiation workers to be 20 mSv per year averaged over defined periods of five years. In addition, the ICRP recommended the annual equivalent dose of 20 mSv for the lens of the eye, 500 mSv for skin, and 500 mSv for hands and feet [9, 10, 11].

1.2 Problem Statement

NM uses radionuclides for the diagnosis and management of several health conditions. The increasing importance of radionuclides may become a significant source of occupational radiation exposure and contamination [12]. There are national and international guidelines to ensure that medical radiation exposure and contamination are monitored, and that acceptable limits are adhered to in departments employing ionising radiation. Ionising radiation is a form of radiation with enough energy to potentially cause damage to deoxyribonucleic acid (DNA) and increase a person's lifetime risk of developing cancer. Currently, TLD badges are used for monitoring the exposure to radiation workers in our institution, but the information about each staff member is only obtained after the TLD badges are read.

This project's focus was to use a hand-foot-clothes contamination monitor to assess real-time contamination from commonly used radionuclides on hands, feet, and clothing of the staff in the NMD at the Charlotte Maxeke Johannesburg Academic Hospital (CMJAH). Such a contamination monitor may assist in monitoring of contamination, which can lead to exposure of staff to radiation unaware.The Departments of Medical Physics and NM have to ensure that the radiation exposure received by staff is as low as reasonably achievable (ALARA). The use of a hand-foot-clothes contamination monitor in this project will provide us with the status of our department regarding handling and adherence to proper procedure concerning the radiation safety of staff.

This study's expected outcome is to propose methods that will minimise the contamination of staff in the department. The data obtained will be compared with the current acceptable limits in the country and with the international atomic energy agency (IAEA) or International Commission on Radiation Units (ICRU) safety guidance [13, 14, 15, 16]. The contamination monitor was calibrated both at the beginning and end of the study to eliminate non-reliability.

This study is the first of its kind locally and on the African continent to the best of our knowledge.

1.3 Research question

Is the radiation contamination of staff at the Department of Nuclear Medicine (DNM) in CMJAH a reality? If so, is there a need to improve staff safety and protection by introducing a rigorous method to monitor best practices that minimise contamination and exposure?

1.4 Aim and Objective of the study

This study seeks to assess contamination due to emitting radionuclides on the hands, feet and clothing of different staff members in the NMD. The following must be done to achieve the aim of the study:

- Determination of the radionuclide contamination level of each staff member.
- Compare the contamination level among different staff categories (doctors, radiographers, nurses, general workers and students).
- Determination of the area contributing to high contamination.

1.5 Outline of this dissertation

The purpose of this study is based on radionuclide contamination and minimising radiation exposure to staff as a result of contamination in NM. This study consists of five chapters.

- Chapter One introduces the NMD and the radionuclides used in the department. It summarises the benefit of using radionuclides for patients and the disadvantages for staff. It also provides a statement problem for this study.

- Chapter Two is a literature review. It describes radioactive contamination and how a NMD should be designed. It also focuses on contamination, decontamination, radiation dose and the derived limit for contamination.
- Chapter Three provides information on the materials and data collection required for the project and the methodology used to carry out this study.
- Chapter Four provide the results obtained, followed by analysis and discussion of results.
- Chapter Five deals with the conclusion, recommendations, and limitations of the study.

Chapter 2

Literature review

In this chapter, previous works related to this study regarding radioactive contamination in a NMD are described. In addition, the decay of radionuclides, the interaction of radiation with matter, radioactive contamination and personnel dosimetry are fully explained.

Radioactive contamination on surfaces frequently exceeds the limit during aerosol administration and provides the necessity for wearing gloves and protective clothing. Hands have the most significant radioactive surface contamination since they are generally close to the patient's mouth, frequently holding the aerosol delivery tubing by Mackie et al [17]. Skin contamination can lead to an increase in skin dosage, particularly when using ^{18}F-FDG, resulting in a potentially large impact on the skin dose. The measured activities from skin ranged from 211 Bq/cm^2 to 460 kBq/cm^2, resulting in the cumulated skin dose of 0.02 mSv to 809 mSv. These findings of contamination were for ^{99m}Tc-labelled radiopharmaceuticals and ^{18}F-FDG. However, the study by Cover et al. Only focused on ^{99m}Tc and ^{18}F radionuclide, the same radionuclides were used in our study in the NM department at CMJAH [18]. Hence, care should be taken to avoid radioactive contamination as it interrupts the workflow in the NMD [19]. The workflow is interrupted because the staff is not allowed to enter in the vicinity of the contaminated surface, as it will lead to unjustified exposure to staff. Also, radioactive contamination on the surface will be detected by the gamma camera or PET/CT scan, which will result in doctors not being able to report the cases in the department.

2.1 Decay of radionuclide

Radioactivity was first discovered by Antonio Henri Becquerel in 1896 [20]. Radioactive decay is a natural process that occurs when an unstable parent nucleus transforms by emitting particles or electromagnetic radiation to a stable or unstable daughter nucleus. The unstable daughter nucleus continues with transformation or decay to a stable granddaughter nucleus. The decay continues until the nucleus is stable. The transformation can be understood by using the mathematical expression of radioactive decay. The number of atoms decaying per unit time is proportional to the unstable atoms (N) present [10, 20].

$$\frac{\Delta N}{\Delta t}\alpha N \tag{2.1}$$

$$\frac{\Delta N}{\Delta t} = \lambda N \tag{2.2}$$

where lambda (λ) is a constant of proportionality known as the decay constant. The negative sign indicates that the number of decaying nuclei is decreasing. If in a sample ΔN and Δt are very small, then they can be replaced by the corresponding differentials dN and dt. Then Eq 2.2 can be expressed as: [10, 20]

$$\frac{\Delta N}{\Delta t} = -\lambda N \tag{2.3}$$

Equation 2.3 is a differential equation that can be solved and results in an exponential expression for the number of radioactive nuclides present at a particular time. This differential equation is expressed in terms of integral expression as

$$\int_{No}^{Nt} \frac{dN}{N} = -\lambda \int_{0}^{t} tdt \tag{2.4}$$

$$N_t = N_0 e^{-\lambda t} \tag{2.5}$$

However, activity is the number of atoms undergoing nuclear transformation per unit time [20]

$$A_t = -\lambda N \tag{2.6}$$

where the traditionally SI unit of activity is Curie [21] defined as 1 Ci = 3.7x10^{10} disintegrations /sec (Bq)although the actual Si unit id Becquerel, putting equation Eq 2.6 to 2.5 resulting in the following expression [10]

$$A_t = A_0 e^{-\lambda t} \tag{2.7}$$

Where:

- N_t is the number of radioactive atoms at time t
- A_t is the activity at time t,
- N_o is the initial number of radioactive atoms,
- A_o is the initial activity,
- e is the base natural logarithm (e = 2.718),
- λ decay constant, and
- t is time

Four radioactive decays are used in medical imaging during the transformation of the nucleus when the atomic nucleus undergoes decay [11].

1. Beta (β^{-minus}) emission

   A process where a neutron in the nucleus is transformed into a proton and an electron. For example

   $$n \longrightarrow p^+ + e^- + \bar{v} + energy \tag{2.8}$$

   In the nucleus the electron and positron are ejected and carry away the energy released in the process [10, 11]

2. β^+ emission

   A process where a proton in a nucleus is transformed into a neutron and positively charged electron, for example

$$p^+ \longrightarrow n + e^- + \nu + energy \tag{2.9}$$

   In the process, the positron and neutrino are ejected from the nucleus; the positron loses its kinetic energy in a collision with the atoms of surrounding matter and comes to rest within a few millimetres. However, the positron combines with an electron in an annihilation reaction [10, 11].

3. Electron Capture (EC) decay

   A process where the nucleus captures an orbital electron that will convert proton into a neutron. For example

$$p^+ + e^- \longrightarrow n + \nu + energy \tag{2.10}$$

   The emitted neutrino in a nucleus carries away some of the transition energy. The remaining energy appears in the form of characteristic x-ray and Auger electrons [10, 11].

4. Isomeric Transition decay

   A process that takes place when a daughter is formed in an excited state during radioactive decay. For example

$$^{Am}_{z}\mathrm{X} \longrightarrow {}^{A}_{z}\mathrm{X} + energy \tag{2.11}$$

   The gamma rays are emitted as the daughter nucleus undergoes an internal rearrangement and transitions to a lower energy state [10, 11].

2.1.1 Radioactive Decay Half life

Half-life is the time required by radioactive atoms to decay into half of the initial number of radioactive atoms. The remaining number of radioactive atoms in a sample is [10].

$$N = \frac{N_0}{2^n} \tag{2.12}$$

where n is the number of half-lives that have elapsed. Putting Eq 2.12 into a fundamental exponential Eq 2.5 results in

$$\lambda = \frac{\ln 2}{t_{1/2}} \tag{2.13}$$

where $t_{1/2}$ represents the half-life of a specific radionuclide. Equation 2.13 shows that a half-life is inversely proportional to the decay constant. The range of a half-life is from billions of years to fractions of seconds. The radionuclides used in the DNM have half-lives ranging from a few hours to days.

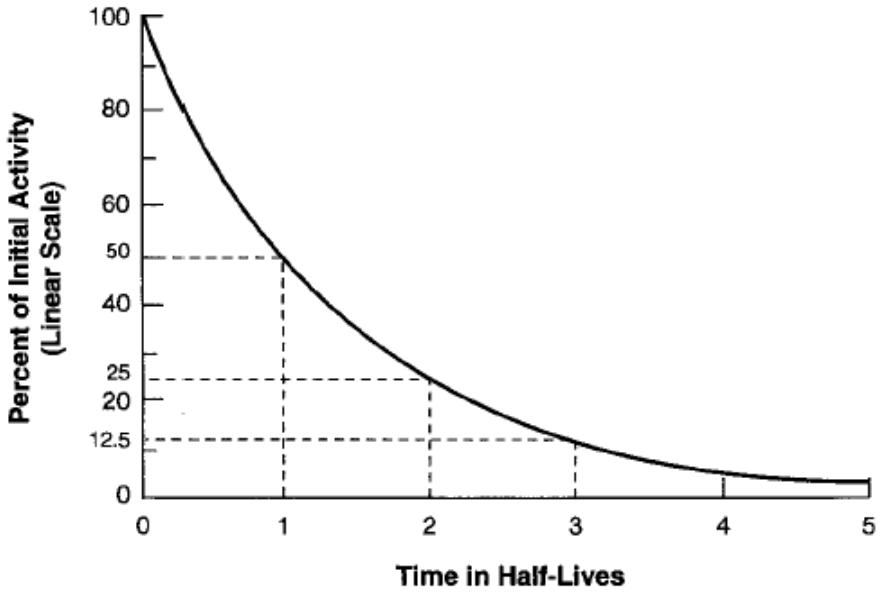

Figure 2.1: Graph of initial activity in percentages with half-life. This plot represents a linear axis of activity as a function of time, resulting in a curvilinear exponential relationship in which the total activity asymptotically approaches zero [10].

2.2 Nuclide used in nuclear medicine at CHJAH

The three most commonly used nuclides in the NMD at CMJAH, South Africa, are:

- Technetium-99m (^{99m}Tc)
- Fluorine-18 (^{18}F)
- Iodine-131 (^{131}I)

Technitium-99m and Fluorine-18 are used for diagnostic purposes. ^{99m}Tc plus a specific radiopharmaceutical are used for imaging cases such as bone scans and myocardial cases. ^{18}F-FDG is used for imaging heart and brain patients. However, ^{131}I is used for diagnostic and therapeutic purposes, depending on the amount of activity given to the patient. Two or five mCi of ^{131}I are used for imaging thyroid cancer. However, a high activity of ^{131}I, such as 30 mCi and upwards, is used to treat differential thyroid cancer. NECSA supplies all radionuclides used in the department at CMJAH. In addition from commonly used nuclides in NMD at CMJAH Iodine-123 ^{123}I is used radionuclide for diagnostic purposes.

2.2.1 Technetium-99m (^{99m}Tc)

(^{99m}Tc) is produced from the decay of Molybdenum-99 (^{99}Mo), which has a half-life of 67 hours [11]. Equation 2.14 illustrates the β-minus decay mode of (^{99}Mo)

$$^{99}_{42}\mathrm{Mo} \longrightarrow {}^{99m}_{43}\mathrm{Tc} + {}^{0}_{-1}\mathrm{e} + \bar{\upsilon} \tag{2.14}$$

^{99m}Tc is a metastable nuclear isomer of ^{99}Tc that decay by isomeric transition to its ground state [10]. Depicted in Fig. 2 2, ^{99m}Tc has energy of 142.7 keV above ground state of ^{99}Tc. ^{99}Tc is a stable nuclear that has a half-life of 2.12×10^{5} years. There are three gamma rays $\gamma1$, $\gamma2$ and $\gamma3$ of photon

energy 2.2 keV, 140.5 keV and 142.7 keV respectively, and are emitted during the decay of ^{99m}Tc. The most common photon energy is the energy of $\gamma 2$, produced in approximate 88% of all transitions and with approximate 12% of other transition. The photon energy of 140.5 keV is suitable to be detected by gamma camera imaging. ^{99m}Tc has physical half-life of 6.02 hours [10, 11].

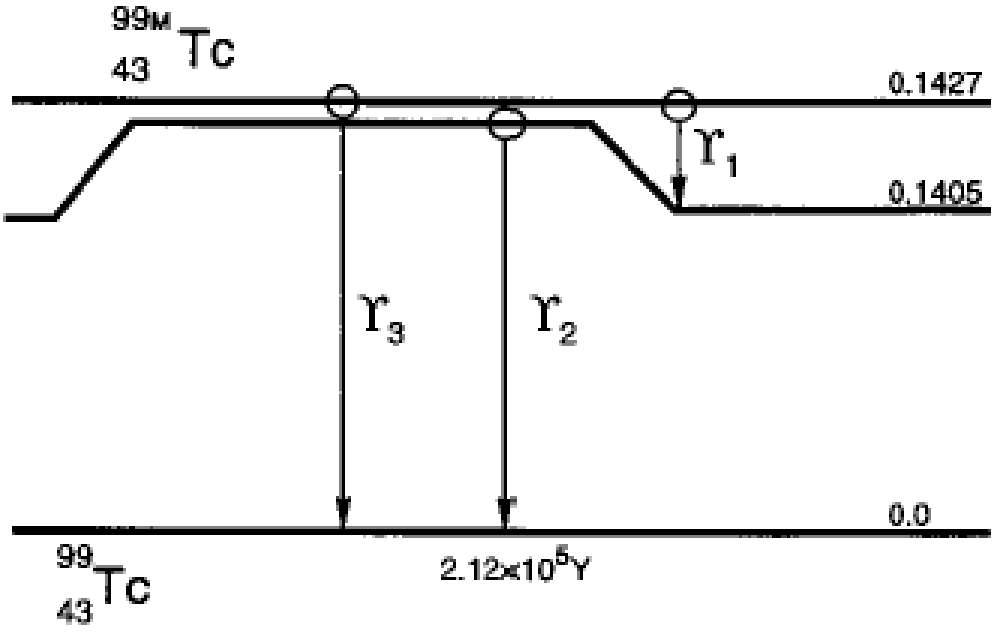

Figure 2.2: Nuclear level scheme showing isomeric transition of ^{99m}Tc to its ground state [10]

2.2.2 Fluorine-18 (^{18}F)

^{18}F is a radionuclide used in nuclear medicine that undergoes beta plus decay and is known as positron (e^+) emitter. ^{18}F has a physical half-life of 110 minutes [9]. Equation 2.15 illustrates the β^+ decay mode of ^{18}F

$$^{18}_{2}\mathrm{F} \longrightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{1}\mathrm{e} + \nu \tag{2.15}$$

^{18}F is combined metabolically into the body system by an appropriate compound ^{18}F-fluorodeoxyglucose (^{18}F-FDG) localised in the body [11]. However,

the positron has a range of a few millimetres in the human body before it combines with an electron from the surrounding tissue. The mass of both e^+ and e^- are converted in an annihilation process that produces two gamma-rays ejected in opposite directions. The photon energy of each gamma-ray is 511 keV [9, 10].

2.2.3 Iodine-131 (^{131}I)

^{131}I is a radionuclide used in NM for the treatment and diagnosis of thyroid cancer [9]. ^{131}I is produced by bombarding stable Tellurium in a nuclear reactor with a neutron particle. It is produced as part of fission products by thermal neutron fission of Uranium-235 in a reactor. ^{131}I decays by emitting gamma rays of 365 keV (81%), 637 keV (7.3 keV) and 284 keV (6.1%), and beta particles with an energy of 606 keV to a stable Xenon-131. Equation 2.16 illustrates the β-minus decay mode of ^{131}I [9, 10, 22].

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e} + \gamma \tag{2.16}$$

Iodine 131 has a physical half-life of 8.04 days and a biological half-life of 120 days[9, 10].

2.2.4 Iodine-123 (^{123}I)

^{123}I is a radionuclide used in the NM department for diagnostic purposes. ^{123}I has a half-life of 13.2 hours and a gamma emission of 160 keV energy. However, ^{123}I is produced by a cyclotron thus it is both expensive and not readily available. ^{123}I gives a lower dose to the patient and with suitable physical characteristics for use in a gamma camera. Therefore, it can replace ^{131}I that is produced by the reactor. The production of ^{123}I has three commonly used methods: ^{123}Te (p, n) ^{123}I; ^{124}Xe (p, 2n) ^{123}Cs $\longrightarrow$ ^{123}Xe and ^{124}Xe (p, pn) ^{123}Xe; ^{127}I (p, 5n) ^{123}Xe $\longrightarrow$ ^{123}I. Iodine produced by these methods is in a suitable chemical form labelling of organic compounds through substitution reactions. However, a small cyclotron with the energy of less than 20 MeV in the energy range of 10−14,5 MeV can be used to produce ^{123}I from the reaction ^{123}Te (p, n) ^{123}I [23].

2.3 Interaction of radiation with matter

The interaction of photons with matter is easily distinguished from charge particles (such as Alpha particles, electrons, Protons) since they are massless and have no electric charge. Photons are electromagnetic radiation with very short wavelengths. Photons may interact with the atom, either with the orbital electron or the nucleus of an atom. There are four crucial basic mechanisms by which photons interact with matter:

- Coherent scattering
- Photoelectric effect
- Compton scattering
- Pair production

Each of these mechanisms has the probability of occurring during the interaction [10]

2.3.1 Coherent scatter

In this interaction, the incoming photon interacts with the entire atom and causes excitation. The incoming photon loses no energy, but it is scattered through a relatively small angle θ with the same photon energy. This scattering angle of a photon increases as the photon energy decreases. Since there is no energy loss, the electrons are not ejected, ionisation does not occur. This process does not play any role in the energy transfer attenuation coefficient and energy absorption coefficient [9, 10, 11]. It is, therefore, not importance in radiation dosimetry. The detection of photons scattered from coherent scattering interactions has a negative effect on image quality. This process occurs mostly in diagnostic X-ray machines with low energy, such as mammography (15 to 30 keV) [10]. Coherent scatter is of little significance in nuclear medicine. Mathematically, the energy of incoming photons is equal to the energy of scatted photons at a small angle. Eq 2.17 and Eq 2.18 show the mathematical relationship.

$$h\nu_{incomingphoton} = h\nu_{scatterphoton} \tag{2.17}$$

$$\lambda_{incomingphoton} = \lambda_{scatterphoton} \tag{2.18}$$

where $h\nu_{incomingphoton}$ is the energy of the incoming photon and $h\nu_{scatterphoton}$ is the energy of scattered photons.

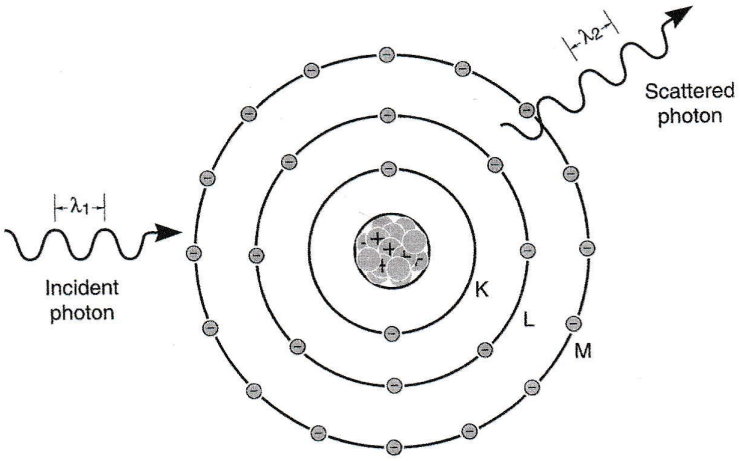

Figure 2.3: A schematic diagram illustrating the coherent scatter. The incoming photon interacts with an atom, and the scattered photon is emitted with the same wavelength and energy. Photons are scattered forward [10].

2.3.2 Photoelectric effect

A photoelectric effect is a process that is dominant at low photon energies (<100 keV) and is the most favoured process for photon spectroscopy. The photoelectric effect happens when an atom absorbs all the incoming photon's energy and ejects one of the orbital electrons in a K-shell of the atom, as illustrated in Fig. 2.4. The energy of the incoming photon required is higher than the binding energy of an orbital electron; therefore, the energy of the ejected electron is equal to the energy of the incoming photon minus the binding energy of the electron. The photoelectron is an ejected electron and is ejected with the kinetic energy given in Eq 2.19 as [20, 24, 25, 26].

$$T_e = E_\gamma - B_e \tag{2.19}$$

where B_e is the binding energy of the electron and E_γ is the total energy of

the incoming photon.

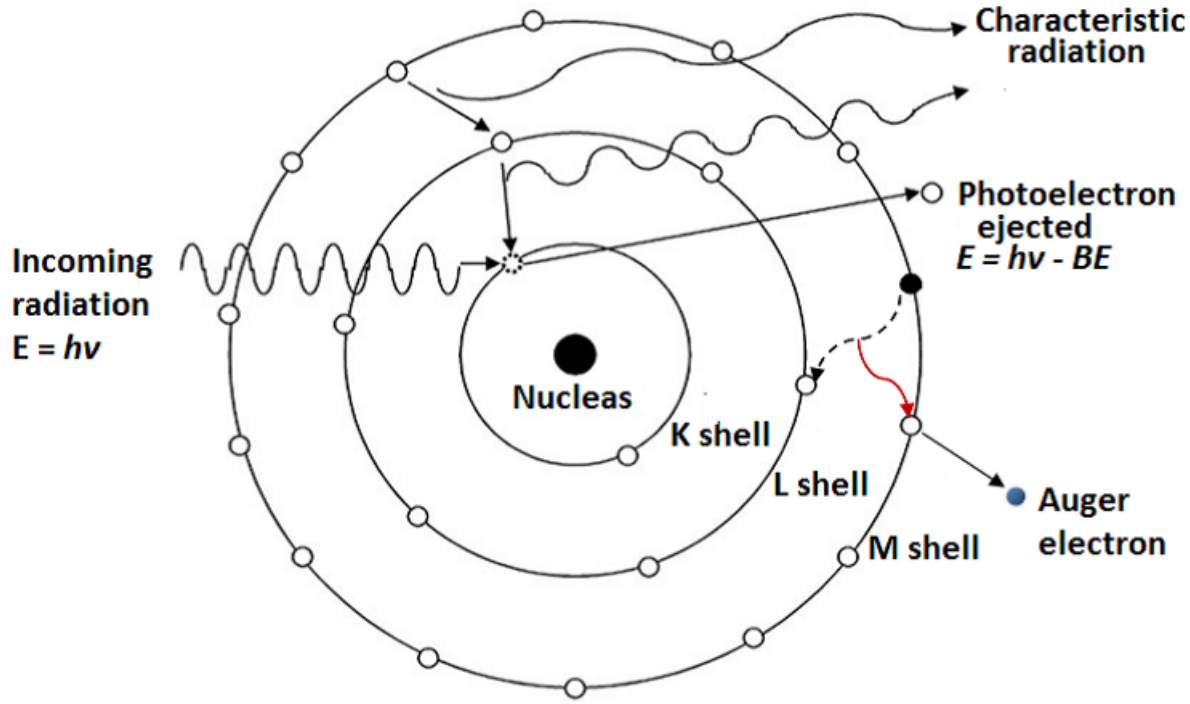

Figure 2.4: A schematic diagram illustrating the photoelectric effect [27]. The incoming photon interacts with the atom and disappears in a process as it transfers all its energy to the photoelectron

When the orbital electron is ejected from the K-shell of the atom, it leaves a hole and also leaves the atom in an excited state. The electron from the higher shell with lower binding energy drops to fill the hole in the K-shell of an atom. This process creates another hole from L-shell, which is filled by another electron with lower binging energy compared to the first one. The process of electron cascade from outer to inner shell takes place. The difference in binding energy results in the emission of characteristic X-ray or auger electrons, as illustrated in Fig. 2.4. The photoelectric interaction is strongly dependent on the energy and atomic number of the material, with the photoelectric cross-section being estimated in Eq 2.20 as [24, 26, 27].

$$\sigma \alpha \frac{Z^n}{E^{3.5}} \tag{2.20}$$

where n is normally between four and five, depending on the material absorbing the photon. The higher-Z material is used for shielding against the photon.

2.3.3 Compton Scattering

In Compton scattering, the incoming photon interacts with the weakly bound orbital electron in the outer shell of an atom. The incoming photon with high energy scatters by an orbital electron at an angle θ with the reduced energy. The electron recoils and carries away part of the photon energy [24, 26].

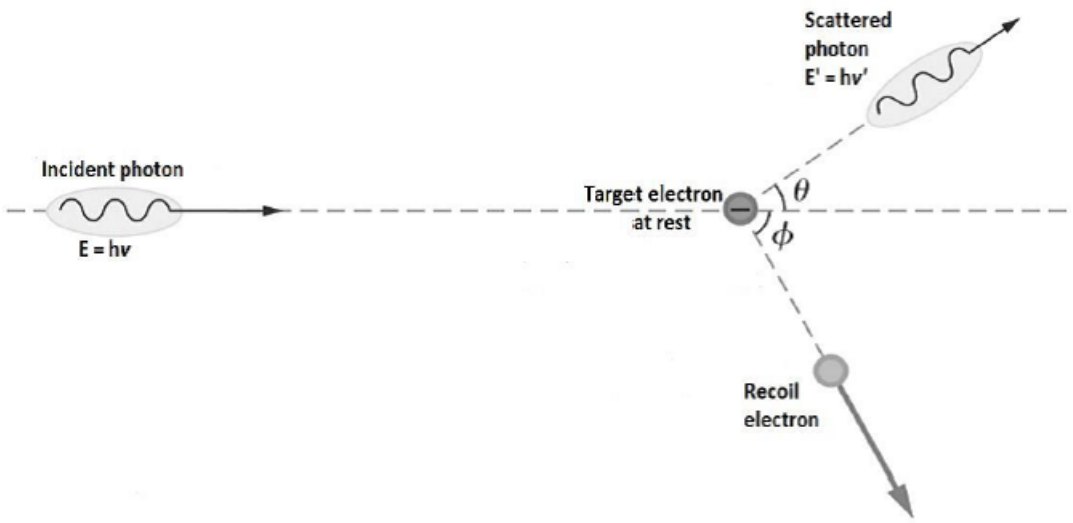

Figure 2.5: A schematic diagram illustrating the Compton scattering[27]. The incoming photon transfers part of its energy to the recoil electron and scatters in a different direction at an angle(θ) [27]

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From the conservation of momentum and energy, the scattered photon energy can be calculated by the expression [20, 24]

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + (\frac{E_{\gamma}}{mc^2})(1 - cos\theta)} \tag{2.21}$$

where the energy of the incoming photon is E_γ, $E_\gamma{}'$ is the energy of the scattered photon, mc^2 is the electron rest mass-energy, and θ is the angle of the scattered photon to the incident photon. The kinetic energy of the electron scattered can thus be expressed in Eq 2.22 as

$$T_e = E_\gamma - B_e = \frac{E'_\gamma(1 - cos\theta)}{mc^2 + E_\gamma(1 - cos\theta)} \tag{2.22}$$

The Compton scattering is most dominant at medium energies of approximately 0.511 MeV. The probability for Compton scattering depends more on the density than on the atomic number of the material and decreases rapidly with increasing photon energy.

If the photon E_γ makes a direct hit with the orbital electron, the electron will travel forward at an angle of 90^o and scattered photon will travel backward direction at an angle of 180^o. Hence, the electron will receive maximum energy $E_{\gamma-}max$ and the scattered photon will be left with minimum energy $T_{e-}min$. Substituting angle $\theta = 180^o$ into Eqs 2.21 and 2.22, one can obtain expressions for energies of scattered photon and scattered electron as written in Eqs 2.23 and 2.24 below

$$E'_\gamma = \frac{E_\gamma}{1 + 2(\frac{E\gamma}{mc^2})} \tag{2.23}$$

$$T_e = \frac{E_\gamma^2}{mc^2 + 2E_\gamma} \tag{2.24}$$

If a photon makes a grazing hit with the electron, the electron will be emitted at right angles ($\phi = 90^o$) and the scattered photon will go forward ($\theta = 0^o$). Therefore, Eqs 2.22 and 2.23 becomes $E'_\gamma = 0$ and $T_e = E\gamma$ [20]

2.3.4 Pair production

In this process, the incoming photon interacts strongly with the electromagnetic field of an atomic nucleus. It gives up all its energy in the process of creating a pair consisting of an electron (e^-) and a positron (e^+). However, the rest mass energy of the electron is equal to 0.511 MeV. The pair production

occurs when the photon has enough energy to exceed the threshold energy of $2mc^2 = 1.022$ MeV. The photon energy is converted into kinetic energy of the particles and the rest mass of the electron and positron as given in Eq 2.25 [20, 24, 28].

$$T_- + T_+ = E_\gamma - 2mc^2 \tag{2.25}$$

T_- and T_+ are the kinetic energies of the electron and positron, respectively. The positron created due to the pair production process loses its energy as it traverses the matter. Near the end of its range, the slowly moving positron combines with one of the free electrons in its vicinity to give rise to two annihilation photons. Two photons with energies of 511 keV each are released. The annihilation photons are emitted in opposite directions for the momentum to be conserved, as illustrated in Fig. 2.6. They may interact in the absorbing medium by photoelectric absorption or Compton scattering [26, 24].

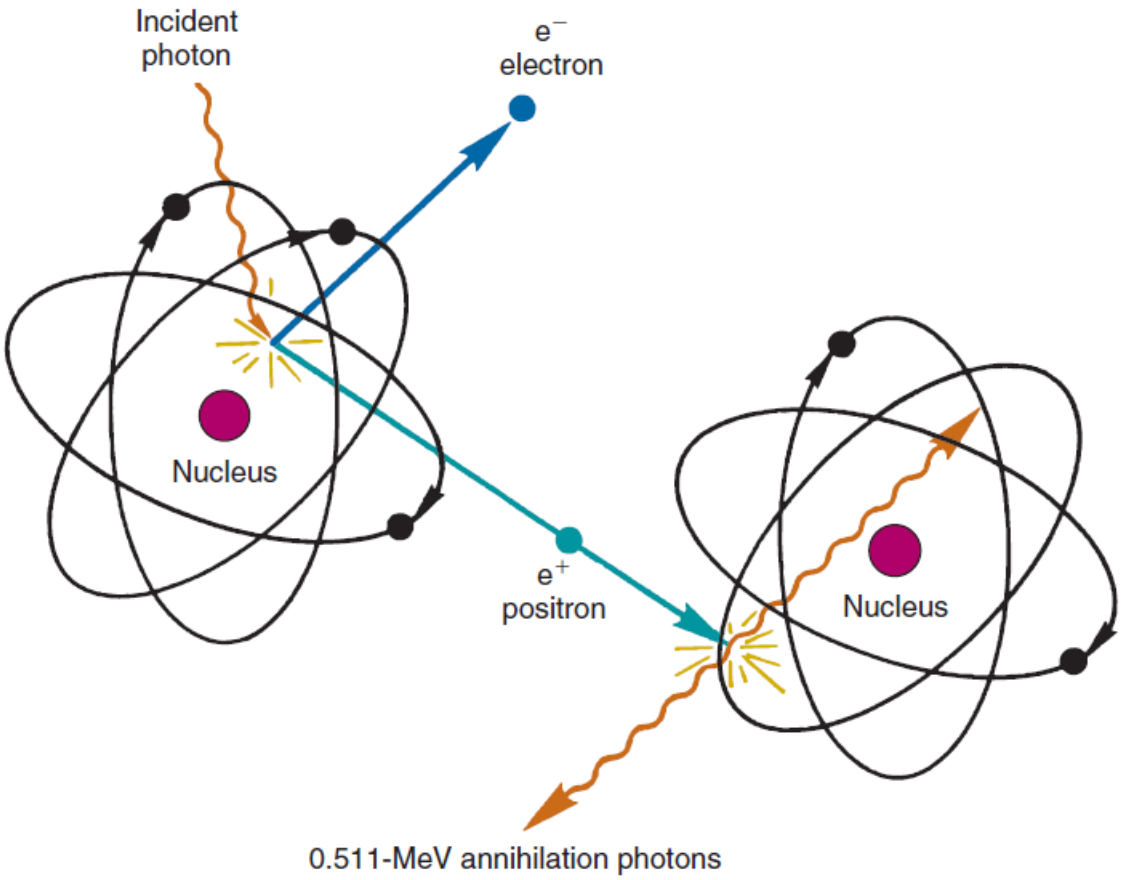

Figure 2.6: A schematic diagram illustrating pair production. The high energy of the incoming photon is converted into electron and positron with their kinetic energy. However, in the end, the positron loss all its energy and combines with the electron, resulting in annihilation photons with 0.511 MeV [43] .

2.4 Radiation Protection in nuclear medicine

The design of a DNM in a hospital or clinic should consider the types of diagnosis and treatment of diseases done and the radioactive materials to be used. The idea of categorising hazards must determine the special needs concerning ventilation, plumbing, materials used in walls, floors and workbenches [9, 29, 30, 31].

2.4.1 Purpose of a design and requirements

The purpose of nuclear medicine department design is based on the following:

- The principle of ALARA of the staff, patient and members of the public.
- Preventing the spread of low, medium and high radioactive contamination around and outside the department.
- Ensuring safe and comfortable accommodation for visitors.
- Maintain low background radiation levels to avoid interference with imaging equipment.
- Ensuring the safety and security of sources [9, 29, 30, 31].

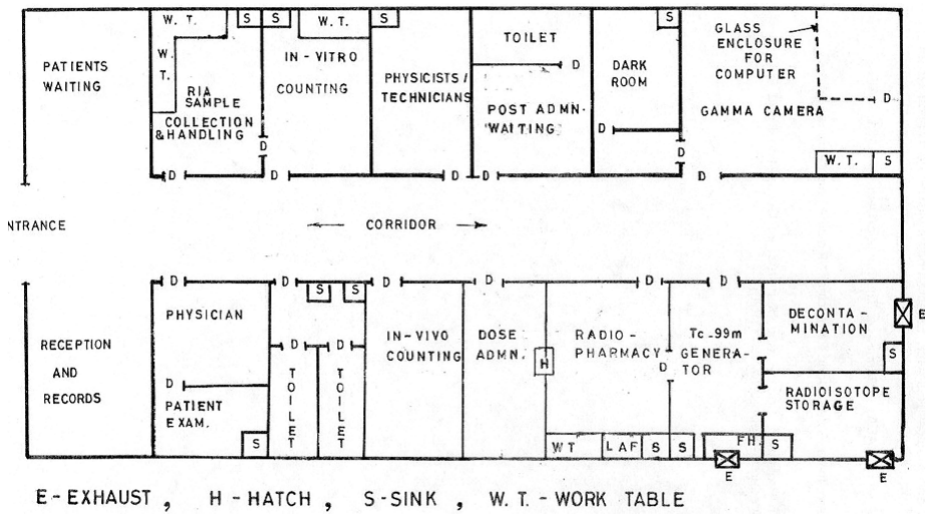

Figure 2.7: An example of the layout of a diagnostic NMD [21]. This layout shows the optimum design in terms of decontamination and minimising radiation exposure.

2.4.2 Floors type

A floor in NM has the potential to be contaminated with radioactive materials. Therefore, the department floor should be covered with continuous smooth and

non-absorbent materials, which can be cleaned and decontaminated easily. In addition, the floor should be chemically resistant to change, curved to the wall, and all joints sealed and glued to the floor [9, 29, 30, 31].

Figure 2.8: Picture showing the floor type in the DNM at CMJAH (with permission of the HOD). The floor is covered with a smooth and non-absorbent material.

2.4.3 Ceiling and wall type

The ceiling and walls should be completed with a smooth and washable surface with joints sealed. The walls must be painted with washable, non-porous paint [9, 29, 30, 31]. The walls and ceiling in the department at CMJAH have a smooth and non-absorbent surface.

2.4.4 Tables and shelves in preparation and administration room

Tables must be robust enough to carry the weight of any shielding materials required for protection from radionuclides. The surface of tables must be a smooth, non-absorbent material, washable and chemical resistant surfaces, all being joint-sealed. Some laminates do not resist certain chemicals, and the supplier should be consulted regarding the specific chemicals to be used in the laboratory. Open shelves should be kept to a minimum to reduce the accumulation of dust. Services (for example, gas, electricity and vacuum)

should not be mounted on top of the bench but on walls or upstands. Light fixtures should be easy to clean and enclosed to minimise dust accumulation [9, 29, 30, 31].

2.4.5 Ventilation system and Fume hood

The use of radiopharmaceuticals administered via inhalation produce radioactive gases or aerosols. Therefore, an appropriate air removal system is required to minimise the internal contamination risk to the staff. The ventilation system must be designed so that the laboratory is at negative pressure relative to surrounding areas. This ventilation system should include a fume hood, laminar airflow cabinet or glove box. The airflow must move from areas of minimal likelihood of airborne contamination to areas where airborne contamination is likely to occur. All air from the laboratory must be vented through a fume hood and must not be recirculated either directly, in combination with incoming fresh air in a mixing system, or indirectly, due to the proximity of the exhaust to a fresh air intake [9, 29, 30, 31]. The material used to build the fume hood should be smooth, impermeable, washable and resistant to chemicals. The work surface must have a slightly raised lip to contain any spills. The air-handling capacity of the fume hood must be designed so that a stipulated minimum face velocity is 0.5 $m.s^{-1}$ and should be tested frequently [9, 29, 14].

2.5 Contamination

In NM, contamination is an uncontrolled radioactive substance found in an unwanted area or part of the body and clothes, leading to radiation exposure to staff, caregivers, patients, and members of the public [10, 19]. Contamination can be classified as external and internal contamination. External contamination can happen on a surface or body of a staff member when encountering solid or liquid radiopharmaceuticals. This contamination can result in both external exposure and internal exposure if the radiopharmaceutical gets into the body. Internal contamination occurs when a liquid or gaseous radiopharmaceutical enters the body through an opening. The contamination limits given in Table 2.1 below were derived based on the annual effective dose limit of 20 mSv per year [9]. The Radiation Protection Officer (RPO) must be informed

when a staff member suspects that internal contamination has occurred.

Table 2.1: The recommended derived limits for surface contamination by ICRP [16] .

Radionuclide	Derived limit (Bq/cm^2)		
	Surface and equipment in controlled areas	Surfaces of the Body	Designated and Public areas, Personal clothing, Hospital bedding
^{75}Se, ^{89}Sr, ^{123}I, ^{131}I	30	3	3
^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{51}Cr, ^{67}Ga, ^{99m}Tc, ^{123}I, ^{111}In, ^{113m}In, ^{201}Tl	300	30	30
^{3}H, ^{14}C, ^{81m}Kr, ^{127}Xe, ^{133}Xe	3000	300	300

Table 2.2: Allowed level of surface contamination measured over the average area 100 cm^2 by Directorate Radiation Control in South Africa [13] .

	Inactive area, part of the body, clothes, etc Bq/cm^2	active area and protective clothing, glassware etc Bq/cm^2
Alpha emitters	0.3	3
Beta/gamma emitters	3	30

The contamination can occur at any time when a radioactive nuclide is introduced inadvertently in the surrounding space. However, there are consequences of radioactive contamination in nuclear medicine [32] which include

- Unnecessary radiation exposure of staff, patients, caregivers and members of the public in NMD.
- The probability of transferring radioactive contamination from a controlled to an uncontrolled area enlarges the area to be decontaminated.
- There is a likelihood of disturbing the patient imaging timetable in the imaging rooms as they need to be decontaminated, and the waiting time of the patients and caregivers increases.

There are ways to avoid radioactive contamination from coming into contact with staff and ensuring no transfer of contamination to other areas in the department. The techniques involve wearing laboratory coats, plastic gloves and closed shoes for protection against radioactive contamination [10]. The following safety procedures must be adhered to:

- Routine survey of radioactive contamination of staff and work surfaces.
- The surface where radiopharmaceuticals are used must be covered by the absorbent material, which is changeable when contaminated.
- Volatile radiopharmaceuticals must be kept in a fume hood to prevent airborne contamination and inhalation.
- Gloves must be discarded in a labelled radioactive waste bin by the staff after using radiopharmaceuticals.
- Staff must wash their hands before eating or drinking and after handling the radioactive materials to minimise potential exposure and internal contamination.
- Plastic material must cover gamma camera collimators to prevent contamination of the detectors.

There is one important advantage of working with radiopharmaceuticals compared to other hazardous materials: it is easily detected, even in small quantities. It is effective when the department has a suitable contamination monitor for detecting any source emitting radiation [10]. Mathematically, surface contamination can be determined by surface activity. The surface activity given by Eq 2.26 estimates the radioactive contamination [33]

$$A_s = \frac{N - N_o}{E_i.E_s.W.60} \tag{2.26}$$

where A_s represents the surface activity or surface contamination in Bq.cm^{-2}, N is a gross count rate of the measurement in counts per minute (cpm), No is the background count rate in cpm, E_i is instrument efficiency in count per emission, E_s is the source emission efficiency in emission per Bq, W is an area of the detector window in cm^2 and 60 represent time conversion factor in s per min [33].

The definition of E_i is the ratio between the net count of the instrument and the surface emission rate ($q_{2\pi}$) of a source for a specified geometry. Where, $q_{2\pi}$ is the particle fluency that incorporates both the absorption and the scattering processes that affect the radiation emitted from the source. The E_i is only determined during calibration by obtaining a static counting with the detector over a calibration source that has a traceable activity or surface emission rate E_s is the ratio between the number of particles of a given type emerging from the front face of a source and the number of particles of the same type created or released within the source per unit time. E_s takes into account the particle emission increase due to backscatter effects, as well as the decrease to self-absorption losses [33]

2.6 Decontamination

Decontamination is the removal or reduction of contamination by a physical or chemical process [34]. Decontamination must be done until the radioactive contamination is below the derived safe limits for surface contaminations as listed in Tables 2.1 and 2.2, respectively. If the safe limits of contamination are not met or reduced, the surface must be covered or stripped [14].

In terms of personnel decontamination procedures, both hands must be washed after working with radiopharmaceuticals and before leaving a control area due to potential radioactive contamination. If the contamination monitor picks up contamination after hand washing, the surfactant or chelating agent specific to the chemical form of the radioactive contamination must be applied [29, 31].

The Radiation Protection Officer (RPO) must be informed when the part of the body other than the hands is contaminated or when the procedures for decontamination of the hands are ineffective. Precautions must be taken when decontaminating the face to prevent the entry of the radioactive substance into the eyes, nose or mouth [29, 31].

If the skin is broken or has a wound when working with a radioactive substance and gets contaminated by accident, the skin must be rinsed with tap water as soon as possible, ensure not to wash any contamination into the wound. Once first aid procedures have been taken, the staff, caregivers, patients, and members of the public must seek further medical treatment, including removal

of contamination if necessary [29, 31].

If clothes are found to be contaminated, they must be removed as soon as possible and washed separately from other clothes to ensure no spread of contamination. For nuclides with a short half-life, contaminated clothes can be stored for the decay period if recommended [29, 31].

2.7 Radiation Exposure

Exposure is the radiation quantity used to measure ionising electromagnetic radiation produced in the air by gamma or X-ray source. However, the ICRU define exposures in terms of the simple formula [20]

$$X = \frac{dQ}{dm} \tag{2.27}$$

where dQ is the absolute value of the total charge of the ions of one sign produced in the air when all the electrons liberated by photons of mass dm are completely stopped in the air. The SI unit of exposure is J/kg, but exposure has a traditional unit called a roentgens (R) [20]. Exposure is so widely used as a quantity of radiation because it can be measured easily. All forms of radiation measurement are based on an effect produced when the radiation interacts with a material. The specific effect used to measure exposure is the ionisation in air produced by the radiation [35]. The exposure is measured by placing an ionisation chamber at the point of measurement. Inside the chamber is a volume of air. When a small volume of air is exposed to ionising radiation (such as photons), some photons will interact with the atomic shell electrons. The interaction results in a knockout of the electrons from the atom, producing an ion pair. When the negatively charged electron is removed, the atom becomes a positive ion. Within a specific mass of air, the quantity of ionisation produced is determined by two factors, the concentration of radiation photons and the energy of the individual photons [35, 36]. An exposure of one roentgen produces 2.08 x 10^9 ion pairs per cm^3 of air at standard temperature and pressure (STP), and one cm^3 of air at STP has a mass of 0.001293g. The definition of a roentgen is the amount of exposure that will produce ionisation of 2.58 x 10^{-4} Coulomb (C) per kg of air, where a coulomb is a unit of electrical

charge. Since ionisation produces charged particles, the amount of ionisation produced can be expressed in coulombs. One coulomb of charge is produced by 6.24 x 10^{18} ionisations [20, 35].

2.8 Absorbed Dose

The quantity of exposure can only be applied to photons of less than 3 MVe and can only be measured in air [20, 37]. The absorbed dose is introduced as a measure of the biological effects and absorbed dose in the tissue induced by ionising radiation. The quantity of absorbed dose can be defined as the quantity of radiation for all ionising radiation types, including charged and uncharged particles for all materials and energies. When energy is transferred to the electron, not all of it is absorbed in the medium. Some of the energy is radiated away as bremsstrahlung radiation. The absorbed dose is the energy that is absorbed in the medium (tissue or organ), and it is brought about by the ionisation and excitation that occurs in an atom. The ICRU define the quantity of absorbed dose (D) as [20, 37, 38]

$$D = \frac{dE_m}{dm} \tag{2.28}$$

where dE_m is the mean energy imparted by ionising radiation to material of mass dm. The dose values can be in the traditional SI unit of rad used during 1953 or in the current SI unit of Gray (Gy) [20, 37, 38].

The absorbed dose in tissues or organs cannot be measured directly by any practical approach. Dose measuring devices and dosimeters can be placed and positioned on the surface, but it is impossible to insert them into the internal tissues or organs. Indirect methods usually determine the absorbed dose in most body tissues [36].

A routine method is to measure entrance surface exposure or air Kerma over the tissue or organ of interest and then use published dose conversion factors to calculate the dose in a specific tissue location. Another method used to determine dose is actually to measure the dose in a phantom. A phantom is a block of some material (usually plastic or water) with the same radiation absorption properties as tissue. The phantom should be approximately the

same size and shape as the body section in which the dose is to be determined. A dosimeter is inserted into the phantom, which is exposed to radiation using known exposure factors. The measured dose values in the phantom can then be used to estimate patient dose values by applying appropriate factors to account for different exposure conditions. It is not always easy to determine the absorbed dose to a specific tissue location or organ in a patient undergoing an imaging procedure. There are several complicating factors, including variations in organ size, location, body size and composition and the non-uniformity of radiation distribution within the body [36].

2.9 Biological effects

The amount of energy of ionising radiation deposited on the tissue or organ has a biological effect as it interacts with living matter. It can kill cells or cause damage which may later lead to malignancy or other detrimental functional changes in the exposed tissues and organs [9]. However, not all ionising radiation types have the same potential to produce biological damage to irradiated tissues. For example, 1 Gy of one type of ionising radiation might produce more radiation damage than 1 Gy of another type. It was for this reason that ICRU introduced two quantities associated with biological effects. Although they are not directly measurable, they are known as equivalent dose and effective dose. However, contamination and exposure must, therefore, be taken into consideration for staff in the department because it might increase the damage on the cell or kill cells [9].

2.10 Equivalent dose

Equivalent dose (H) is the product of the absorbed dose and radiation weighting factor [10]. It can be expressed as

$$H = D \times W_R \tag{2.29}$$

where D is an absorbed dose and W_R is the radiation weighting factor. An equivalent dose is a quantity that considers the biological effect, which occurs

due to radiation interacting with tissues or organs. Tissue damage per Gray of the absorbed dose depends on the type of radiation and its energy and how it is deposited on the tissue. For example, heavily ionising radiation such as alpha (α) and neutrons cause greater harm to tissues and organs than photons and electrons at the same average absorbed dose. This is because the alpha particle deposits its energy in a short-range, and photons and electrons do so over a wider area. Photons, electrons, and positrons have a radiation weighting factor of one. This implies that the equivalent dose in medical imaging is equal to the absorbed dose and, therefore[9] [11]

$$H = D \tag{2.30}$$

The personnel exposure in a radiation science facility is determined and recorded as dose equivalent. The SI unit for the dose equivalent is a Sievert (Sv).

2.11 Effective dose

The effective dose is a radiation quantity that expresses relative risk on humans and is used for patients, occupational workers and members of the public. An effective dose looks at specific organs and areas of the exposed body because not all parts of the body and organs are equally sensitive to the possible adverse effects of radiation. The effective dose (ET) for a specific organ or part of the body is: [35]

$$E_T = D \times W_T \tag{2.31}$$

where D is an absorbed dose and W_T is an assigned tissue weighting factor, which differs between organs. However, if more than one organ or part of the body has been exposed, the effective dose is the sum of the products of the equivalent dose or absorbed dose to each organ or tissue irradiated and the corresponding weighting factor for them as indicated in Eq 2.32 [35]

$$E_T = \Sigma W_T \times H \tag{2.32}$$

2.12 Dosimetry

Dosimetry is the measure of radiation from individuals to determine their radiation dose equivalent precisely. When radiation interacts with the human body, there are no immediate effects. Without using a personnel dosimeter, radiation workers could unknowingly be exposed to excessive amounts of ionising radiation, which could lead to cell damage [39].

2.13 Personnel dosimeter

A personnel dosimeter is a device worn by radiation workers on the chest or waist to measure radiation from radioactive material. There are two types of personal radiation monitoring,

- TLD badge
- A pocket dosimeter

TLD badges are used to measure cumulative ionising radiation doses over weeks or months. Pocket dosimeters provide an immediate readout of measured ionising radiation and can, therefore, be used for a short period.

2.13.1 Theory of ThermoLuminescent Dosimeter (TLD)

TLDs were developed during the 1970s. TLDs are inorganic crystals such as lithium fluoride (LiF) and manganese-activated calcium fluoride (CaF2:Mn) that produce light when heated. LiF is the most used TLD because it has an effective atomic number of 8.31, close to that of tissue, which makes it more suitable to be used by medical workers. If the TLD is exposed to ionising radiation, it absorbs energy and electrons from the TLD crystal move from the valence to the conduction band. A few electrons return rapidly to the valence band while others are trapped in the intermediate energy level supplied by the impurities in the crystals. The excited electrons leave holes in the valence band, and the trapped electrons can remain in the intermediate level for weeks or months [37, 38, 40].

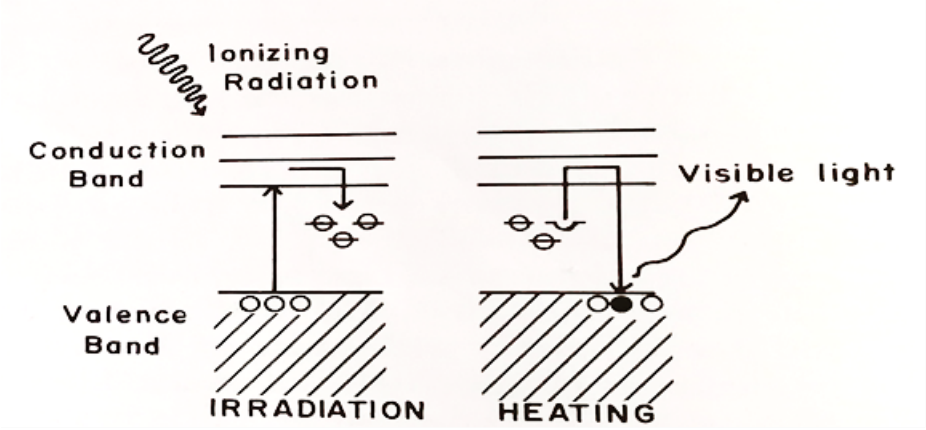

Figure 2.9: Transitions of the electrons taking place on the TLD when exposed to radiation and heated. The electrons from TLD jump from the valence to the conduction band when irradiated. They move back to the valence band and emit visible light when the TLD is heated [37] .

When the TLD is heated in the oven, it causes the electrons to move from the intermediate energy level to the conduction band. In the conduction band, electrons fall back to the valence band, emitting light. The amount of emitted light is absorbed by the photocathode of the photomultiplier tube (PMT). This light is proportional to the number of electrons trapped in the intermediate energy level, which is proportional to the amount of energy absorbed from radiation. The photomultiplier tube converts the amount of light into electrical current to be amplified and measured. The emitted light is plotted with time, as shown in Fig. 2.10 [37, 38, 40].

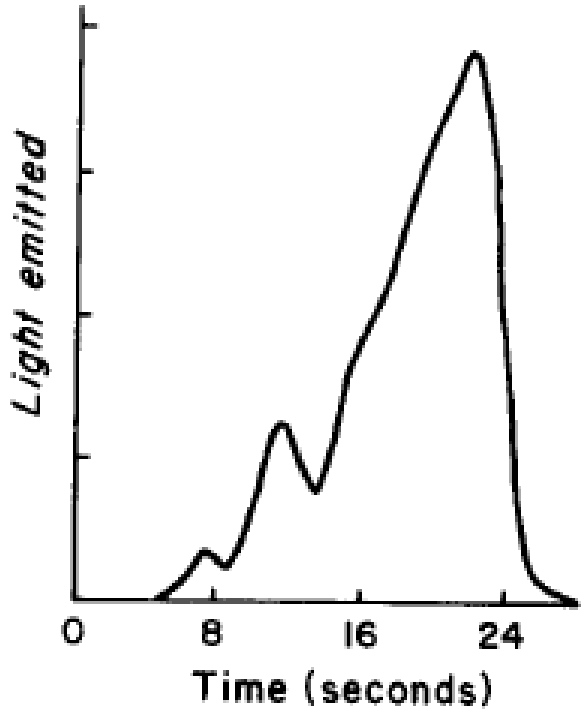

Figure 2.10: The plot of light emitted against temperature is known as a glow curve [38]

The peaks in the curve correspond to the different trapped energy levels. The area under the entire curve is used to measure the radiation dose [37, 38].

2.14 Geiger-Müller detector

A Geiger Müller detector (GM detector) is a gas-filled detector manufactured to detect and measure all types of ionising radiation, such as alpha and beta particles and photons. It consists of two electrodes surrounded by a volume of gas. Generally, a GM tube's container wall is a negative electrode (cathode) that holds the gas together. The positive electrode (anode) is the wire in the middle container, as shown in Fig. 2.11. The gas used in the tube is usually helium or argon at a low pressure [10].

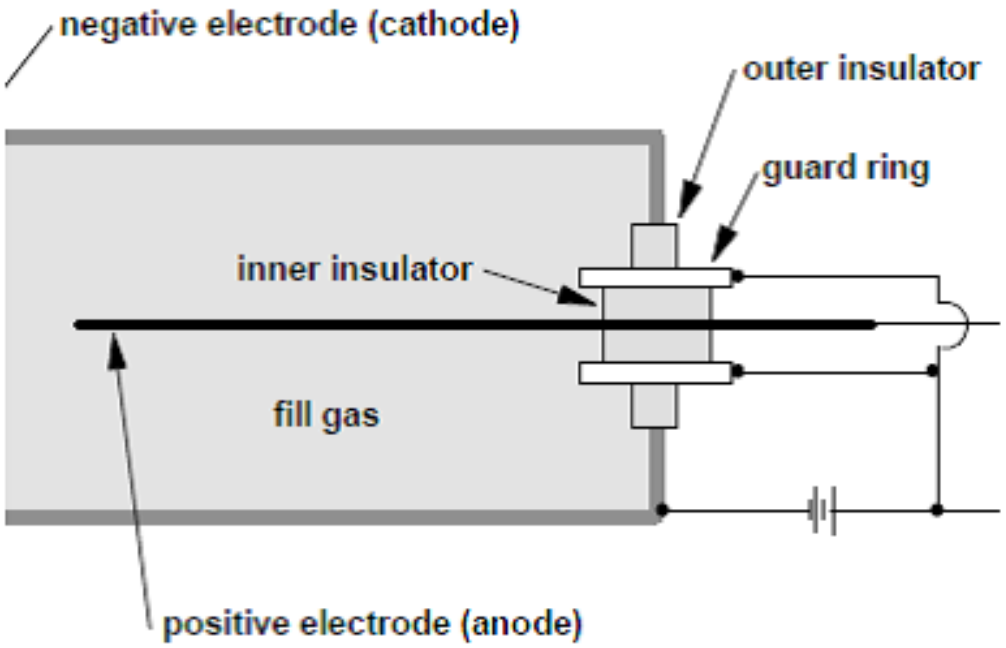

Figure 2.11: A schematic diagram showing the basic structure of a gas-filled detector [41].

When the radiation enters the tube, it ionises some gas molecules. The electrons of the ionised atom in the gas are knocked out of the atom and leaving it with positively charged ions. The high voltage applied in the GM tube produces an electric field, electrons are quickly attracted to the positive electrode, and positively charged ions are attracted to the negative electrode. This process produces a pulse of electric current in a wire connected to the electrodes, and the pulse is recorded. The charged ions are neutralised after the pulse has been recorded, and the GM counter is ready to record another pulse. If there is no voltage applied between the electrodes, there is no electric field to attract the particles to the electrode, leading to an absence of current flow. However, when an applied voltage is too low, the positive ions tend to take longer to be collected by the negative electrode due to their low mobility. The presence of positive ions results in numerous distortions of the electric field. Any event that occurs when the electric field is distorted will either produce no pulse at all or a pulse with small amplitude which is only partially detected by the counting system. A minimum electric field is required to collect the negative charge and produce any pulse in the tube [10, 42].

2.15 Inverse square law

The radiation from a radioactive point source is emitted isotropically, that is, with equal intensity in all directions. However, the flux of intensity (I) of radiation from the point source decreases as the distance increase. At a distance r from a point source of gamma ray emitting radioactivity, the emitted radiation passes through the surface of an imaginary sphere having a surface area: $A = 4\pi r^2$. The flux I of radiation passing through the sphere per unit of surface area, in units of γ-rays/sec/cm^2 is [43, 10]

$$I = \frac{\varepsilon}{4\pi r^2} \tag{2.33}$$

Where ε is the emission rate of the source and r is given in centimeters. If the emission rate from a source is ε_1 at distance r_l, at another distance r_2 the emission rate ε_1 will be [43]

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{r_1}{r_2} \tag{2.34}$$

The relationship in the equation above is valid only for point sources whose dimensions are small with respect to the distances r_1 and r_2. However, this relationship would not be valid near (less than 1 m from) a radioactive point source. Inverse square law has an important implication for detection efficiency as well as for radiation safety considerations. The application of inverse-square law in radiation safety is to maintain a larger distance that reduces the exposure rate emitted from the radioactive point source to staff. The inverse-square law applies to all types of radioactive emissions [43, 10].

Chapter 3

Materials and Methods

This chapter describes the materials and methods used to collect and manage data, statistical analysis and ethical considerations. The chapter first describes the materials used in section 3.1. This is followed by the details on how the data was collected and the roles of each professional participant in Section 3.2.The radioactive contamination data is categorised according to the profession, time of day, period, location, and radionuclide.

3.1 Material

The materials used to measure contamination of the staff, the response of detectors and exposure to the staff in the department were:

- Hand-foot-clothes contamination monitors (Mod. CMS60D×D),
- ^{99m}Tc point source,
- A locally self-made stand ruler, and
- TLD Badge personnel dosimeter from South African Bureau of Standards (SABS)

3.1.1 Hand-foot-clothes contamination monitors (Mod. CMS60D×D)

The CMS60D×D hand-foot-clothes contamination monitor has five Geiger-Müller (G-M) detectors as shown in Figure 3.1, which comprise one pair of R×D 1000T foot and hand fixed detectors and one mobile R×D 270 clothes detector to the specification shown in Table 3.1. The monitor is designed to carry a maximum weight of 150 kg on its footboard. Beyond this weight, the detectors might be damaged. Foreign objects in the protection grates can also damage the monitor as the detector surfaces are extremely sensitive. Special care of the detectors should be taken when a person steps on to the monitor.

Figure 3.1: Picture showing the CMS60D×D hand-foot-clothes contamination monitor available in the NMD of the CMJAH. This monitor was manufactured by TEMA Sinergie.

The geometry surface area of all five detectors is 100 cm2. The detectors are

tightly sealed and filled with high purity xenon (Xe). The case of each detector is made of aluminium (Al), and the window is made of titanium (Ti). The CMS60D×D hand-foot-clothes contamination monitor was manufactured in Faenza, Italy, on 11 January 2013 and installed and calibrated at CMJAH by AEC-Amersham, South Africa, in 2013. Calibration was done to check the performance of the monitor in the DNM at CMJAH compared to the manufacturer. The CMS60D×D hand-foot-clothes contamination monitor is designed and built to measure radiation and contamination levels caused by gamma and beta-emitters on hands, feet and clothing. After installation and calibration, staff members in the department were trained on using and operating the monitor.

Table 3.1: Specification of the hand-foot-clothes contamination monitors (Mod CMS60D×D). The specification was obtained from the manual provided by the supplier.

Features	specification		
Input	220V, 50Hz AC		
Max absorbed power	100W		
Dimension	**Detectors**	**R×D 1000T**	**R×D 270**
	Length	394 mm	258 mm
	Height w/o electronics	24 mm	24 mm
	Height with electronics	55 mm	55 mm
	Depth	310 mm	160 mm
G.M with surface front window	250 cm^2		
Lower energy limit	10 keV for gamma rays and 150keV for beta particles		
Window thickness	14mg/cm^2		

3.1.2 ^{99m}Tc point source

An Eppendorf tube and ^{99m}Tc radionuclide was used to make a point source for checking the hand-foot-clothes contamination monitor's response. Section 3.2.2 in the method section provides details on how the response of the detectors was measured.

Figure 3.2: Picture representation of 99mTc point source in an Eppendorf tube.

3.1.3 Locally self-made stand ruler

A 100cm long stand ruler source holder was made from Perspex at CMJAH, and small equidistant holes were made. The distance between holes was measured using the calibrated ruler shown in Fig. 3.3. The calibrated ruler was used to minimise inaccuracies in the distance of the stand ruler. This stand ruler source holder was made in the mould room and workshop of the medical physics department at the CMJA hospital. The stand was made of polystyrene, with a weight of approximately four grams inserted. The weight of the stand was used to balance the ruler, which was attached to the edge of the stand. The point source was placed on the source holder at 3cm, as shown in Figure 3.3. The stand ruler source holder was used to check the response of the detectors.

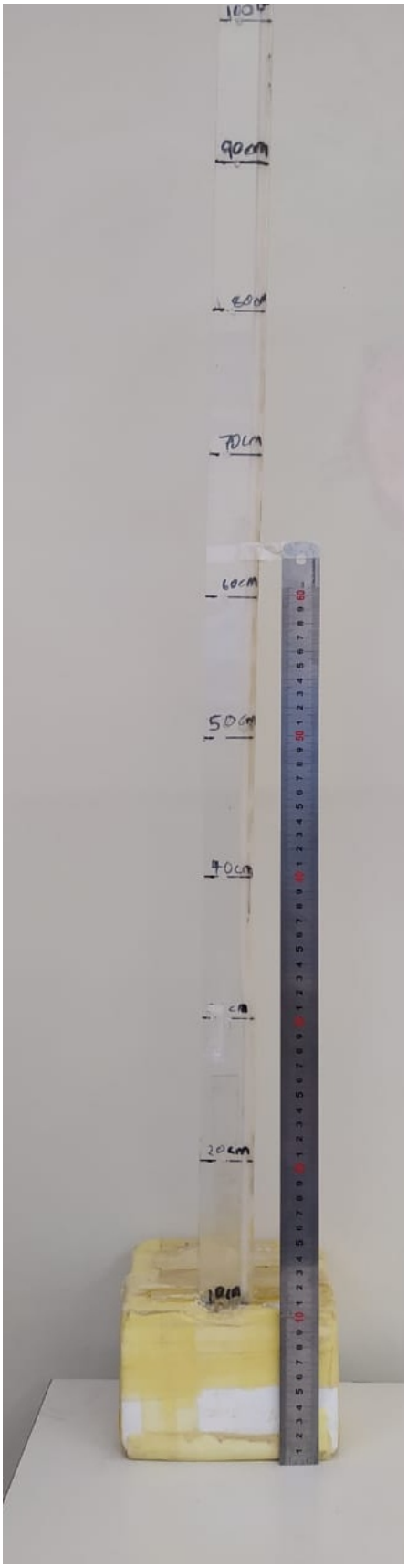

Figure 3.3: Locally made stand ruler source holder made in the mould room and workshop of the medical physics department at the CMJAH.

3.1.4 TLD Badge from SABS

TLD badges are used for monitoring effective whole-body radiation doses to staff in the chosen department. Staff members in the NMD at CMJAH are provided with TLD badges and wear them on the chest or waist to monitor whole-body radiation. The TLDs are used during working hours and kept at home by the staff in a non-radioactive place. TLDs in the department are replaced every 28 days and sent back to the SABS to determine the radiation received by the staff. The dose records are kept in the department to enable individual staff to access their results at any time.

3.2 Methods

3.2.1 Background Measurements

The hand-foot-clothes contamination monitor performed automatic background measurements on five detectors. The background radiation of contamination was subtracted from actual radioactive contamination that was received by staff. Measurements of background contamination were carried out when the unit was switched on in the morning, for a programmable time of approximately 10 seconds, and repeated for an equal period of time after approximately 4 hours. This was because the monitor could not carry out other measurements until it was done measuring background contamination.

3.2.2 Checking the response of detectors

The self-made stand ruler source holder was used to test for detector response on the monitor. To make a point source, ^{99m}Tc was drawn at 11:09 am using a syringe and placed in an Eppendorf tube (see Figure 3.2). The point source's initial activity was measured to be 1.248 mCi of ^{99m}Tc using a dose calibrator. The ruler was placed vertically next to each detector for hands, feet and clothes, as shown in Figure 3.4. The point source was attached to the source

holder of the stand ruler 10 cm from the detector. The first measurement was taken at 11:20 am, from the radioactivity decay in the exponential rate and applying Eq 2.7, the activity of the source was found to be 1.245 mCi. The first measurement was taken by pressing a start button on the monitor to detect radioactive contamination emitted from the source. The distance between the source holder and detector was varied by moving the source holder vertically upward at equal spacing of 10 cm on the ruler. The detector response test was checked more than once. However, due to different activity of a point source of different detector response tests. The point source with an activity of 1.248 mCi was used for this study.

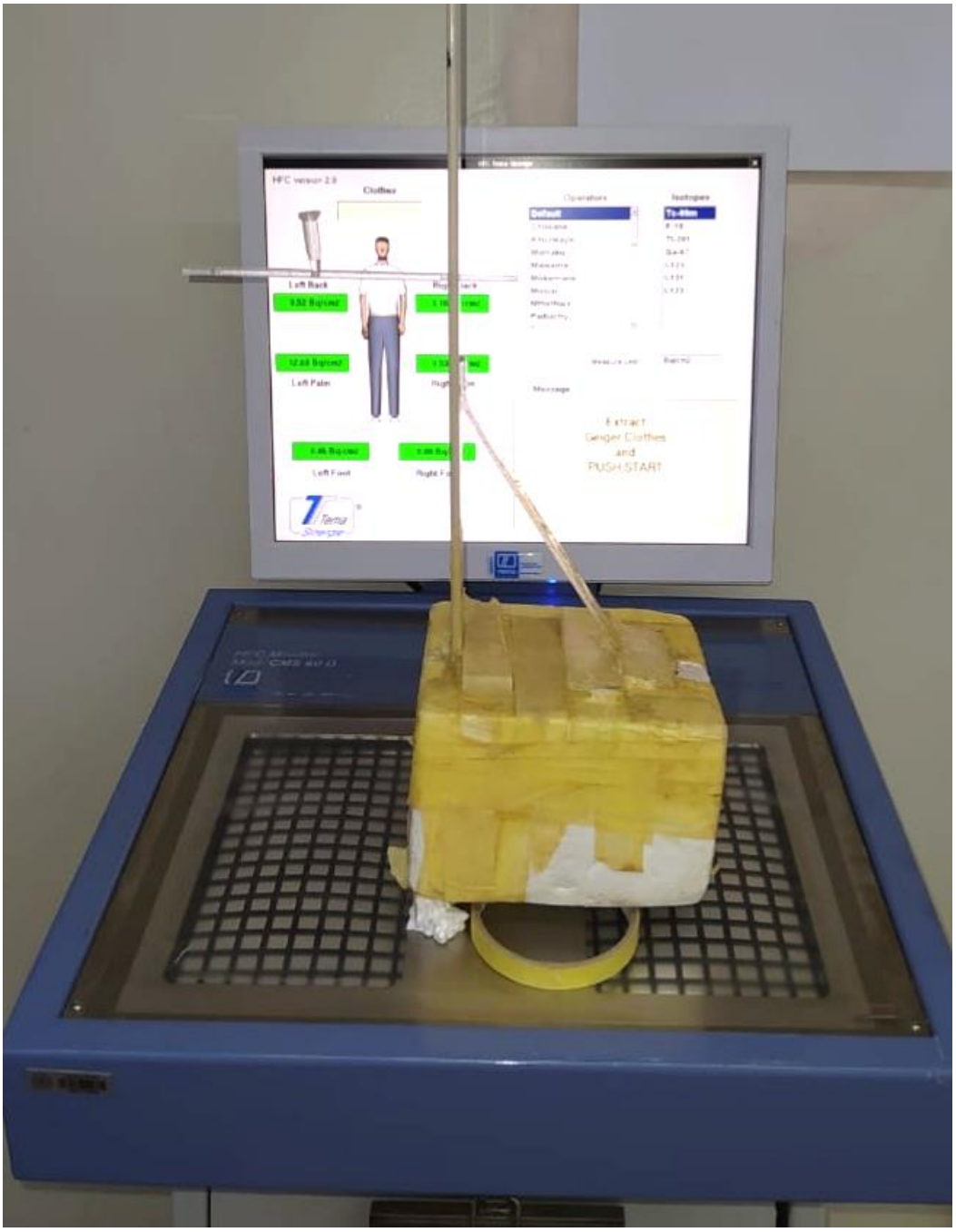

Figure 3.4: Locally made stand ruler source holder placed on top of the contamination monitor.

3.2.3 Staff members consent and confidentiality

All staff working in the NMD at the CMJAH were approached to participate in this project. Those who accepted became participants and signed a consent form. Participant information was kept confidential by giving each participant a code known only to the principal investigator. A sample consent form given to participants is included in Appendix C.

Table 3.2: Number and profession of participants in the study

Profession	Number
Doctors	12
Radiographers	13
Students	5
Nursing	4
Medical physicist	1
Admin support	1
Secretary	1
Cleaners	2
Total number of participants	39

3.2.4 Contamination measurement of participants

All participants were required to use hand-foot-clothes contamination monitors on arrival in the morning, at 11:00 am (beginning of lunchtime), and at 3:00 pm, or just before leaving the department at the end of their day. The process was repeated for every participant for 12 weeks. However, there were two break periods (each for two weeks) when participants were not required to measure contamination. The two weeks period was introduced in the study to guarantee that staff is not proactive in avoiding contamination with time. The first three weeks of taking measurements before the two-week break was called the first period (period 1). The second three weeks of taking measurements before the second two-week break were called the second period (period 2). The last weeks of taking measurements before the after the two-week break was called the third period (period 3).

On arrival, all participants were assumed to be free of any form of contamination as they had not yet been in contact with any radionuclide in the department. The measurement of potential contamination was taken to verify that

hands, feet and clothing were radiation-free and also to determine if participants were receiving any radioactive contamination outside the department. By 11:00 am, and before leaving the department at the end of the day, all participants were busy preparing radionuclides, injecting patients or positioning them in gamma cameras and the PET scanner.

Staff in NMD were allocated to different station for one week or two weeks. Hence, participants were asked which area they are working in before step on the contamination monitor. The rotation of staff in NMD was done to ensure that staff doesn't stay in an area with a high probability of getting contaminated and receiving high exposure for a long time. For example, two staff were allocated to work in a hot lab (where ^{99m}Tc labelled radiopharmaceutical is prepared) for two weeks. After two weeks they are allocated in the admin section where contamination and exposure are minimal. Also based on the allocation of the staff in the department, we knew which radionuclide they are working with when we measure contamination. Simultaneously, participants such as general assistants (GA, referred to as general workers in the results section) clean the floor and the hot laboratory (a specially designed room where the radiopharmaceuticals are delivered, stored and prepared for dispensing). Each participant was actively engaged in their daily activities.

When participants stepped on the contamination monitor and put their hands and feet on the detectors, a start button was pressed for the monitor to start detecting the presence of radioactive contamination. After this step, the mobile detector was moved around the participants' body to detect radioactive contamination in their clothes. The contamination monitor performs a sequence of hands (front and back) measurements, feet and clothing with automatic background subtraction. At the end of this process, the detected radioactive contamination report is shown on the screen. The monitor's readings were recorded and expressed in units of Bq/cm^2 and classified according to location, profession, time of day, period and radionuclide.

3.2.5 Tasks performed by participants

Radiographers performed six tasks:

1. Elute ^{99m}Tc from the generator for the radiographer working with ^{99m}Tc.

2. Measure the total activity eluted from the generator in the calibrated dose calibrator. They also had to measure molybdenum and aluminium breakthrough.

3. Prepare radiopharmaceuticals and the dose to be administered to the patient. These tasks were performed in the hot laboratory, behind a lead shield.

4. Measure radiopharmaceuticals in the dose calibrator and transport them to the injection room.

5. Inject patients and return the used syringes to the shielded wastebasket in the hot laboratory.

6. Position the patient on the gamma camera for imaging.

The tasks for student radiographers were generally similar to the qualified radiographers, depending on their rotation. The task for the GAs was to keep the hot laboratory and the department clean. Nurses were responsible for putting intravenous lines in patients, measuring their vital signs and providing medication when required. Apart from reporting on all studies, Physicians inject specific radiopharmaceuticals for cardiac studies and administer radioactive ^{131}I capsules to thyroid cancer patients in other instances.

3.2.6 Routine measurement of radiation exposure

Apart from the administrator and secretary, all department participants wear TLD badges to monitor radiation for their effective whole-body doses. The TLD badge was worn on the chest or waist of each participant. The results were analysed and returned by the SABS after every wearing period and expressed in mSv.The threshold for SABS is too high for this study since they don't record deep dose less than 0.15 mSv and beta skin dose less than 3.25 mSv. This threshold may have an effect on the low contamination, since it may not be recorded although it was registered.

3.2.7 Data analysis

Data was entered into an Excel sheet from the data collection sheets. The data was imported into Stata Version 15 (Stata Corp) for further analysis. Descriptive statistics was conducted. Categorical variables of the personnel was presented as frequency and percentages. The continuous variables such as the contamination on hands, feet or clothes was presented as mean ± standard deviation or median and interquartile range (if not normally distributed). The trend in prevalence was presented graphically to show the pattern of contamination. Missing information was checked on each variable. Association between categorical variables such profession, time of day, location, period and radionuclide was assessed using the Pearson's Chi-Square or Fisher exact test and proportion difference were calculated. The association between the categorical variables and continuous variables was done with K-Wallis test followed by Dunn's test and Benjamini–Hochberg adjustment. The Benjamini–Hochberg adjustment used in making multiple pairwise comparisons following an omnibus test redefines the meaning of α, which usually represents the probability of falsely rejecting the null hypothesis for one test, within the inferential framework of the hypothesis test. This adjustment leaves α numerically intact but multiplies the p-value. This forms the basis of false discovery rate how the expected rate of false discoveries changes after some pairwise tests are rejected in sequence. The Statistically significant association was set at P-value <0.05.

3.2.8 Data management

A de-identified excel spread sheet was imported, using Stata software version 15, different commands assisted in cleaning the data. Data cleaning processes included checking for duplicates, missing values, recoding and categorising variables. This was a quality assurance process.

Chapter 4

Results, Analysis and Discussions

The aim of of this study was:
To assess contamination due to emitting radionuclides on the hands, feet and clothing of different participants working in the NMD. The main objectives of the study were to determine the radionuclide contamination level of each participant, to compare the level of contamination among different participant categories (doctors, radiographers, nurses, GA and students) and to determine which area contributed to high contamination.

4.1 Background radiation of contamination level

The background radiation of contamination levels of the study were taken daily in the morning using a hand-foot-clothes contamination monitor even though the monitor takes background radiation measurements automatically anytime during the day. The reason for this is because background radiation occurs naturally in the environment. The background reading must be subtracted from detected contamination from each participant to get an actual reading of radioactive contamination.

Table 4.1: Background radiation of contamination level taken using a contamination monitor at NM at CMJAH

Part of the body	Contamination Readings (CPS)	standard deviation
Left hand	11.92	2.38
Right hand	10.40	2.75
Left foot	0.00	0.00
Right foot	10.24	1.72
clothes	7.23	2.59

The external cosmic background radiation around Johannesburg is 0.5 mSv per year (0.0014 mSv per day) [44]. As far as we know, the background radiation of contamination in the NMD at CMJAH has not been measured. Table 4.1 shows that the average background radiation of contamination of 4 detectors is 9.95 cps. During the 12 weeks of our study, the background radiation was recorded ten times. The contamination monitor checked the background daily, and the left foot detector read 0.00 cps for background radiation, so we assumed that there might be a problem.

4.2 Detector response test

The detector response test was performed for five detectors using a ^{99m}Tc point source at the beginning of the study. The response test of the detectors was carried out to ensure that the detectors performed similarly. The distance was varied every 10 cm for the five detectors. The detector response test was checked more than once. However, due to different levels of measured activity of a point source that provide different readings, the decision was taken to select only one reading. The point source with an activity of 1.248 mCi was used for this study. The results in Fig. 4.1 show that the left foot detector was not detecting any contamination in the presence of a ^{99m}Tc point source for different distances. Also, the results from fig.4.1 show a huge difference in contamination readings at the distance of 10 cm. However, as the distance increases the difference in four detectors reading contamination decreases. This is because fig. 4.1 obeys inverse square law which states that the relationship between activity and distance is not valid at the distance of less than 1 m. All measurements done at a distance of 100 cm (1 m) are similar, hence all the

points at this distance are lying on top of each other. Also at the distance of 10 cm, more flux of intensity reaches the detector; hence the detectors do not see the source as a point source.

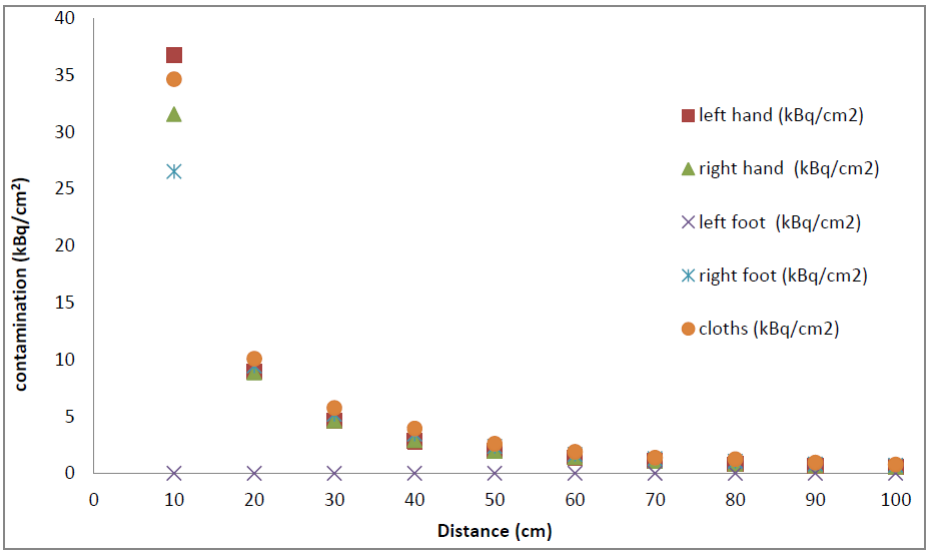

Figure 4.1: The relation between contamination and vertical distance for five detectors

From Fig. 4.1, it was determined that the left foot detector was faulty. The decision was taken to use the right foot detector to measure the left foot contamination and prevent inaccurate measurement of radioactive contamination. The left foot detector reading for background contamination was not added during the calculation of average background radiation. However, before measuring the left foot, a radiowasher was used to decontaminate the right foot detector to minimise errors in reading the potential contamination of the left foot. A service engineer from AEC-Amersham found a puncture on the left foot detector (Figure 4.2). The puncture marks were probably the result of foreign objects such as high heeled shoes.

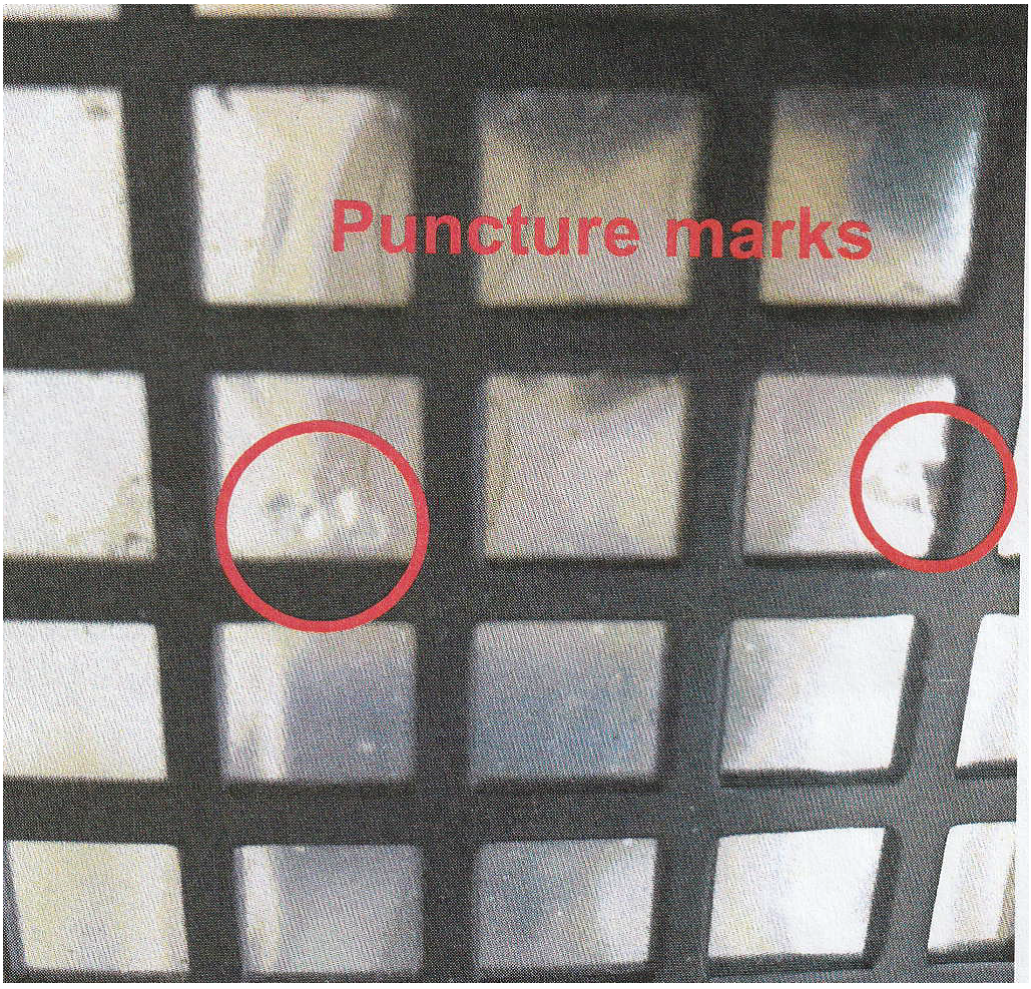

Figure 4.2: Picture representation the left foot detector of contamination monitor with puncture marks on it

4.3 Demographic of our study

Table 4.2 shows that 493 (43%) of the readings were done in the morning by all participants. The first three weeks of measurement for radioactive contamination before the two-week break was called the first period (period 1). In period 1, 599 (53%) readings were recorded. The locations that had the most readings included the gamma camera room 325 (29%), the gamma reporting room 206 (18%), and the gamma injection room 170 (15%), respectively. The most radionuclide readings recorded were for ^{99m}Tc with 917 (81%) and ^{18}F, with 183 (16%) of all the readings done. Of the total number of readings,

there were 436 (38%) radiographer readings, 292 (26%) doctor readings and 170 (15%) nurse readings. The study indicated that radiographers had the highest number of observations 436 (38%) as there were more of them in the department compare to other professions. The time of the day category was statistically insignificant (p=0.053). This may be because most of the staff did not check radioactive contamination before leaving the department, but constantly checked in the morning and at lunchtime. For example, GAs did not check radioactive contamination when leaving the department. The period, radionuclide and location were statistically significant.

Table 4.2: The number of recorded reading for staff with percentage for professions for different times, locations and radionuclide

	Total	Radiographers 436(38)	Students 72(6)	Doctors 292(26)	Nurses 170(15)	General workers 44(4)	Secretary 39(3)	Physicist 39(3)	Admin 45(4)	p-value
Time of day										
Morning	493(43)	174(40)	30(42)	137(47)	75(44)	21(48)	15(38)	17(44)	24(53)	
Lunch	433(38)	177(41)	28(39)	102(35)	67(39)	23(52)	15(38)	11(28)	10(22)	0.053
Departure	211(19)	85(19)	14(19)	53(18)	28(16)	0	9(23)	11(28)	11(25)	
Period										
1	599(53)	233(53)	14(19)	186(64)	81(48)	26(59)	14(36)	25(64)	20(44)	
2	318(28)	98(23)	58(81)	67(23)	43(25)	13(30)	12(31)	12(31)	15(33)	< 0.0001
3	220(19)	105(24)	0	39(13)	46(27)	5(11)	13(33)	2(5)	10(23)	
Radionuclide										
^{99m}Tc	945(83)	361(82)	72(100)	204(70)	167(98)	20(45)	39(100)	37(95)	45(100)	
^{18}F	183(16)	73(17)	0	84(29)	0	24(55)	0	2(5)	0	< 0.0001
^{123}I	9(1)	2(1)	0	4(1)	3(2)	0	0	0	0	
Location										
Gamma camera	325(29)	228(52)	60(83)	0	0	0	0	37(95)	0	
Hot lab	68(6)	56(13)	12(17)	0	0	0	0	0	0	
Office front	49(4)	49(11)	0	0	0	0	0	0	0	
Dexa	28(2)	28(6)	0	0	0	0	0	0	0	
Pet CT hot lab	75(7)	73(17)	0	0	0	0	0	2(5)	0	
Office	39(3)	0	0	0	0	0	39(100)	0	0	
Passage	20(2)	0	0	0	0	20(45)	0	0	0	< 0.0001
Pet Passage	24(2)	2(1)	0	0	0	24(55)	0	0	0	
Admin office	47(4)	0	0	0	0	0	0	0	45(100)	
Gamma reporting	206(18)	0	0	206(71)	0	0	0	0	0	
Pet reporting	86(8)	0	0	86(29)	0	0	0	0	0	
Gamma injection room	170(15)	0	0	0	170(100)	0	0	0	0	

4.4 The frequency of radioactive contamination

Table 4.3 lists the radioactive contamination frequency. The contamination frequency was approximately 92% normal in all categories of suspected radiation contamination from radionuclides. There was approximately 8% moderate contamination on the clothes compared to 4% high contamination of clothes. The predictive probability of contamination across different professions is shown in Fig. 4.3, for which the **Normal margin** was 0.93(0.91-0.94), **Moderate** 0.03(0.02-0.04) and **High** 0.04(0.03-0.05)

Table 4.3: Contamination frequency was classified into normal, moderate and high

	Normal [N (%)]	**Moderate** [N (%)]	**High** [N (%)]
Left hand	1051(93)	38(3)	47(4)
Right hand	1048(92)	37(3)	51(4)
Left foot	1048(92)	49(4)	38(3)
Right foot	1055(93)	41(4)	39(3)
Clothes	993(88)	94(8)	47(4)

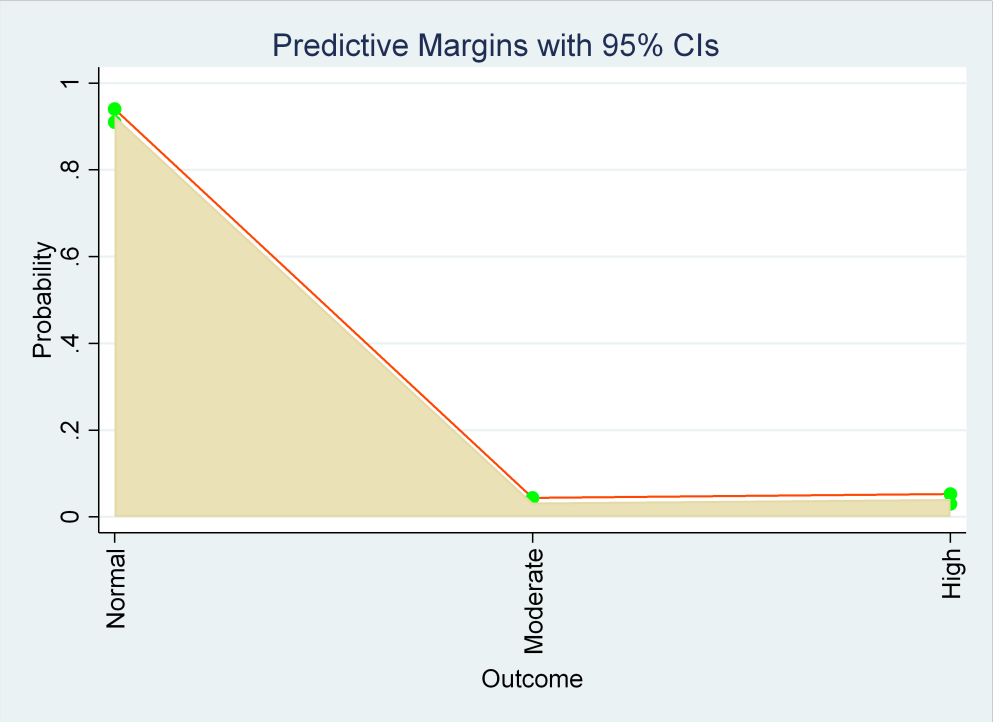

Figure 4.3: The projected probability of detected contamination across different profession

Table 4.3 and Figure 4.3 summarise the results of all the data collected in terms of normal, moderate and high detected contamination. Normal represents detected radioactive contamination from 0 Bq/cm^2 to 30 Bq/cm^2, moderate 31 Bq/cm^2 to 100 Bq/cm^2 and high 101 Bq/cm^2 to ∞ Bq/cm^2. In the normal category, 93% of the left hand, 92% of the right hand, 92% of the left foot, 93% of the right foot and 88% of the clothes detected radioactive contamination. The study showed that normal results are comparable to the derived limits for surface contamination shown in Tables 2.1 and 2.2. [14, 16, 13] Fig. 4.3 at 95% predictive margins is in line with published data [14, 16, 13]. Although moderate and high are not within the derived limits, it might have resulted from a minor spill that happened without staff and students noticing. Therefore, it is vital to continue checking radioactive contamination of the staff and keep the levels below the derived limit for surface contamination at all times. Regular checks of detected radioactive contamination improve working conditions and practices to minimise radioactive contamination, which leads to minimising the radiation exposure to the staff and students.

4.5 contamination categories

Five categories of radioactive contamination were clarified in this study. These categories are: Contamination per profession, Contamination per time of day, Contamination per period, Contamination per location, and Contamination per radionuclide. However, the data that was used to plot figures 4.5, 4.7, 4.9, 4.11 is found in Appendix B.

4.5.1 Contamination per profession

The detected radioactive contamination for the different professions in the department was considered. Among all the participants, it was found that radiographers had the highest detected radioactive contamination in the left and right hands, as shown in Fig. 4.4, which also indicates that radiographers have high radioactive contamination compared to the other professions. Students are the second group with high contamination. The reason for this

is that radiographers and students are actively involved in the preparation of radiopharmaceuticals, injecting patients, performing ventilation/perfusion (V/Q) and positioning the patients in the gamma camera and Positron Emission Tomography (PET) scanner. Also, the high detected contamination may indicate that minor spills were occurring during preparation without radiographers and students being aware of it. Less contamination in students than qualified radiographers was noted because they assist the radiographers but are usually not primary participants in most radiography activities. Doctors and nurses have the subsequent highest detected radioactive contamination. The reason for this could be that the doctors administer radiopharmaceuticals for cardiac and thyroid cases. The nurses had high contamination on the left foot caused either by the contaminated floor or direct minor spillage.

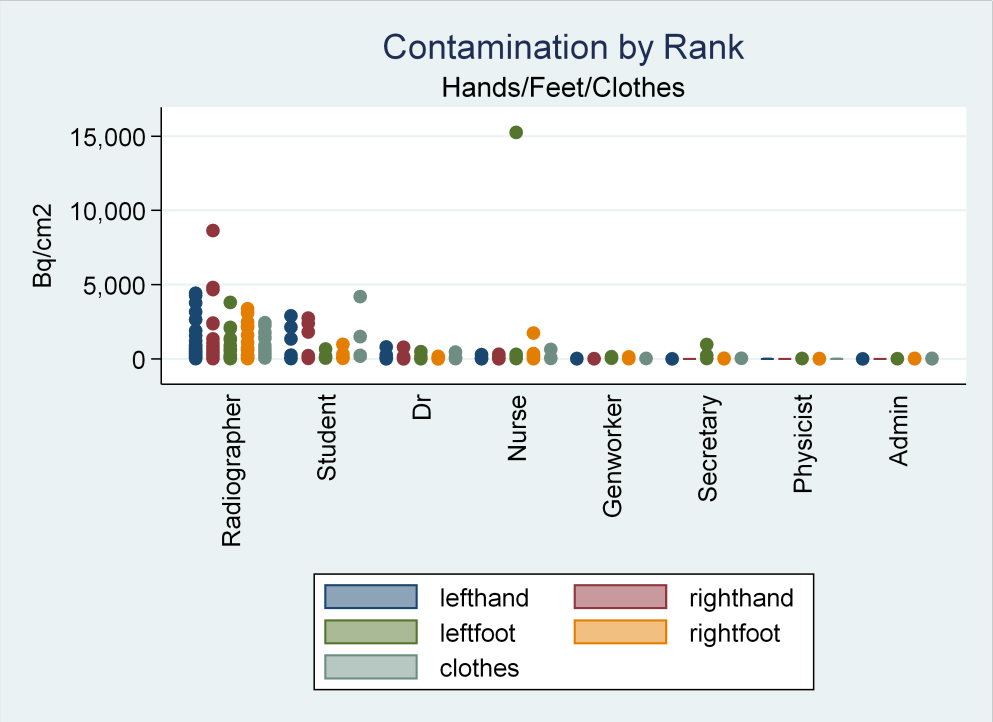

Figure 4.4: Relationship between the detected contamination of hands, feet, clothes and different professions

The results shown in Table 4.4 summarise the detected contamination after the results were adjusted using the Benjamini-Hochberg test for the non-parametric K-Wallis. The study showed that the median and interquartile

(IQ) range for all rankings in Table 4.4 is within the derived limits for surface contamination. There was an exceptional median and interquartile range for students' clothes that was 12.9 (4.4-39.7) Bq/cm^2 and was the highest on clothes. This exception had a 3^{rd} quartile of 39.7 Bq/cm^2 and is above the derived limits of surface contamination [14, 16, 13]. These results indicated statistical significance for detected radioactive contamination after correction with the Benjamini-Hochberg test. Also, our study shows the difference in proportion where statistical significance was noted. The radiographer's left hands were more contaminated than the doctors by a factor of 17. Student's clothing was more contaminated than the doctors by a factor of 4 (Fig. 4.5). These differences were the highest on the profession versus detected contamination. The following abbreviations are used in Fig. 4.5:

- RD - radiographers and doctors,
- RN - radiographers and nurses,
- RG - radiographers and general workers,
- RS - radiographers and secretary,
- RP - radiographers and medical physicist,
- RA - radiographers and administrator,
- SD - students and doctors,
- SN - students and nurses,
- SG - students and general workers,
- SS - students and secretary,
- SP - students and medical physicist,
- SA - students and administrator,
- DS - doctors and secretary,
- NS - nurses and secretary,
- NP - nurses and medical physicist,
- NA - nurses and administrator.

Table 4.4: Median and IQ range for contamination of hand, foot and clothes of the participants

Rank	Left hand (Bq/cm^2)	Right hand (Bq/cm^2)	Left foot (Bq/cm^2)	Right foot (Bq/cm^2)	Clothes (Bq/cm^2)
Radiographer	1.7(0-8.2)	1.2(0-8.3)	0.3(0-7.4)	0.6(0-8)	7(1.6-24.5)
Student	2.8(2.8-9.2)	2.5(0-15.2)	4.9(0-22)	4.8(0-16.8)	12.9(4.3-39.7)
Dr	0.1(0-2.8)	0(0-1.9)	0.02(0-4.1)	0(0-1.6)	3.3(0.4-8.5)
Nurse	0.6(0-3.9)	0(0-3.8)	1(0-9.2)	0(0-7.3)	6.9(3.1-16)
Gen worker	0.1(0-3.6)	0.4(0-4.2)	0.2(0-6.6)	0(0-5.1)	8(2.7-14.6)
Secretary	0(0-2.1)	0.9(0-3.9)	1.8(0-4.7)	0(0-4.7)	5.8(2.8-13.9)
Physicist	0.08(0-4.5)	0(0-3.1)	0.2(0-6)	0(0-1.2)	5.7(1.9-11)
Admin	0(0-2.1)	0(0-3)	1.6(0-5.5)	0(0-5.1)	3.6(1.5-6.4)
p-value	0.0001	0.0001	0.0005	0.0001	0.0001

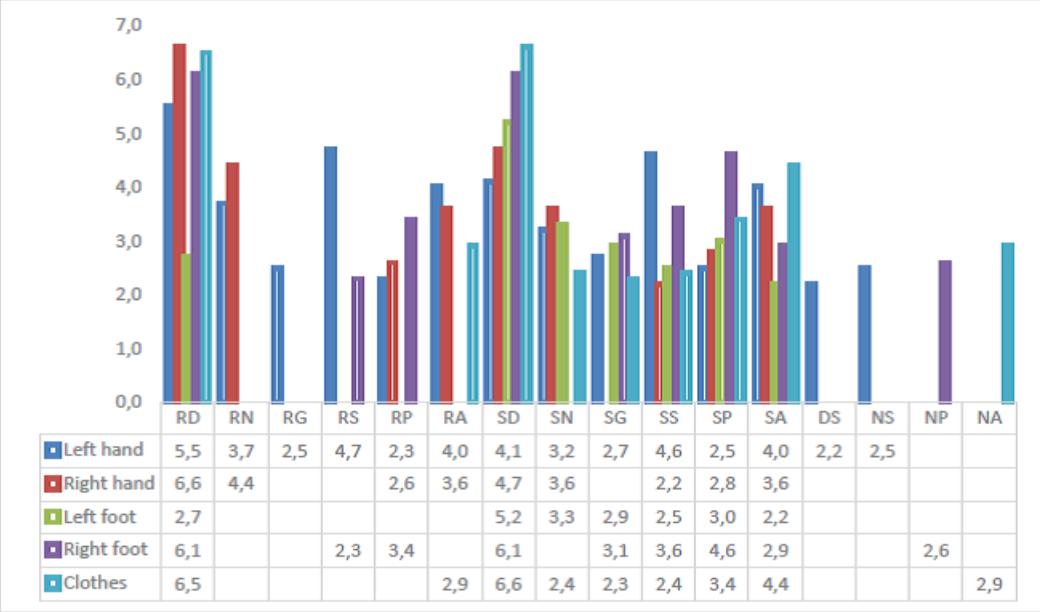

Figure 4.5: The proportion after adjustment for different profession.

4.5.2 Contamination per time of the day

Figure 4.6 summarises the results of detected contamination by the time of the day. During the morning, the detected radioactive contamination is minimal as the participants have not been in contact with radionuclides as yet. This minimal contamination also indicates that the participants do not receive radioactive contamination outside work. At lunchtime, there are high readings of detected radioactive contamination on hands, feet and clothes. This happens because participants have been busy preparing radionuclides, injecting, stressing patients and positioning them in gamma cameras and the PET scanner. At the end of the working day, referred to as knock off time in Fig. 4.6, the detected radioactive contamination is lower due to there being less work and also because of radionuclide decay. There was exceptionally high contamination detected on the left foot during departure time which was probably due to a direct spill, as previously suggested.

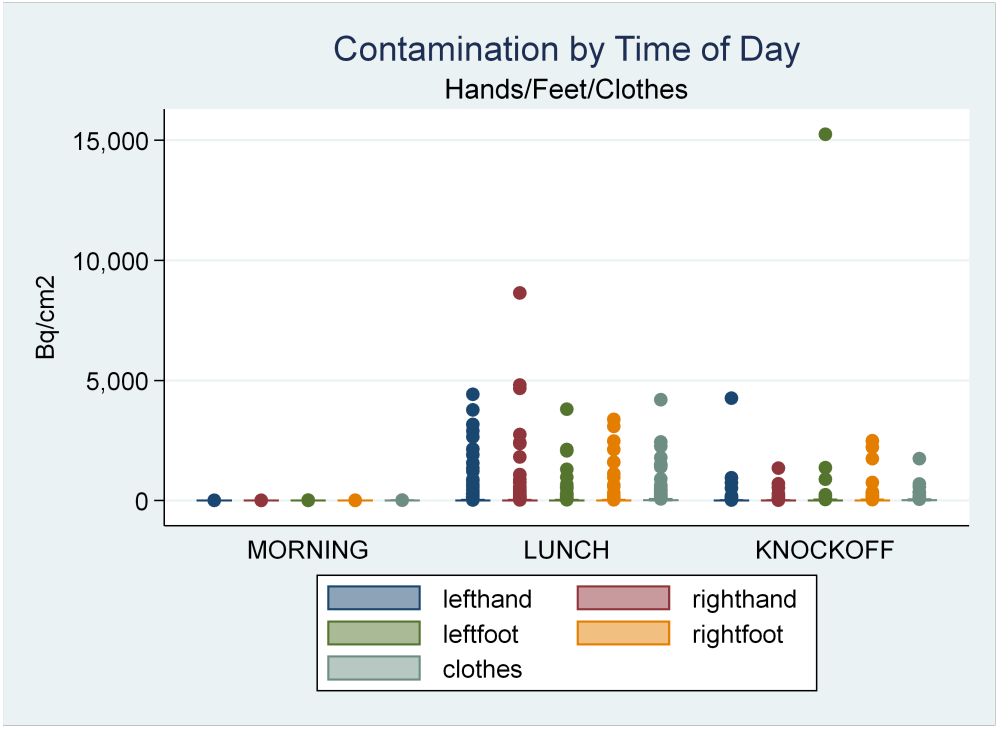

Figure 4.6: The activity of detected contamination on hands, feet and clothing according to the time of the day.

The results in Table 4.5 summarise the detected contamination after the results were adjusted using the Benjamini-Hochberg test for non-parametric K-Wallis. The median and interquartile range obtained for body surface and personal clothing is within the derived limit for surface contamination published nationally and internationally [14, 16, 13]. Lunchtime has the highest median and interquartile range, followed by departure time for the reason given in 4.1.6 above. During lunchtime, clothes had the highest median and interquartile range of 14.7 (5.2-30.2) Bq/cm^2. After adjustment of results using the Benjamini-Hochberg test, the results indicated a statistical significance for detected radioactive contamination (Table 4.5). Figure 4.7 shows that there were negative differences in proportion for morning-lunch and morning-afternoon. Where negative differences mean radioactive contamination is low between morning-lunch and morning-afternoon. The difference obtained for radioactive contamination between lunch and afternoon was the highest with 4.4 Bq/cm^2 on the right hand. There was a factor of 5 times less difference for radioactive contamination on clothes between morning-afternoon. Keeping in mind that the negative sign represents less difference and the positive sign represents a high difference in proportion.

Table 4.5: Median and IQ range for detected contamination during the time of day

Rank	Left hand (Bq/cm^2)	Right hand (Bq/cm^2)	Left foot (Bq/cm^2)	Right foot (Bq/cm^2)	Clothes (Bq/cm^2)
Morning	0.1(0-2.6)	0(0-2.1)	0(0-2.1)	0(0-2.2)	2.9(0.9-5.3)
Lunch	2.2(0-9.4)	2.1(0-10.2)	1.8(0-12.6)	0.5(0-12.2)	14.7(5.2-30.2)
Knock off	1.2(0-8.1)	0(0-5.6)	4.4(0-15.6)	3.2(0-14.9)	10.2(2.3-22.1)
p-value	0.0001	0.0001	0.0001	0.0001	0.0001

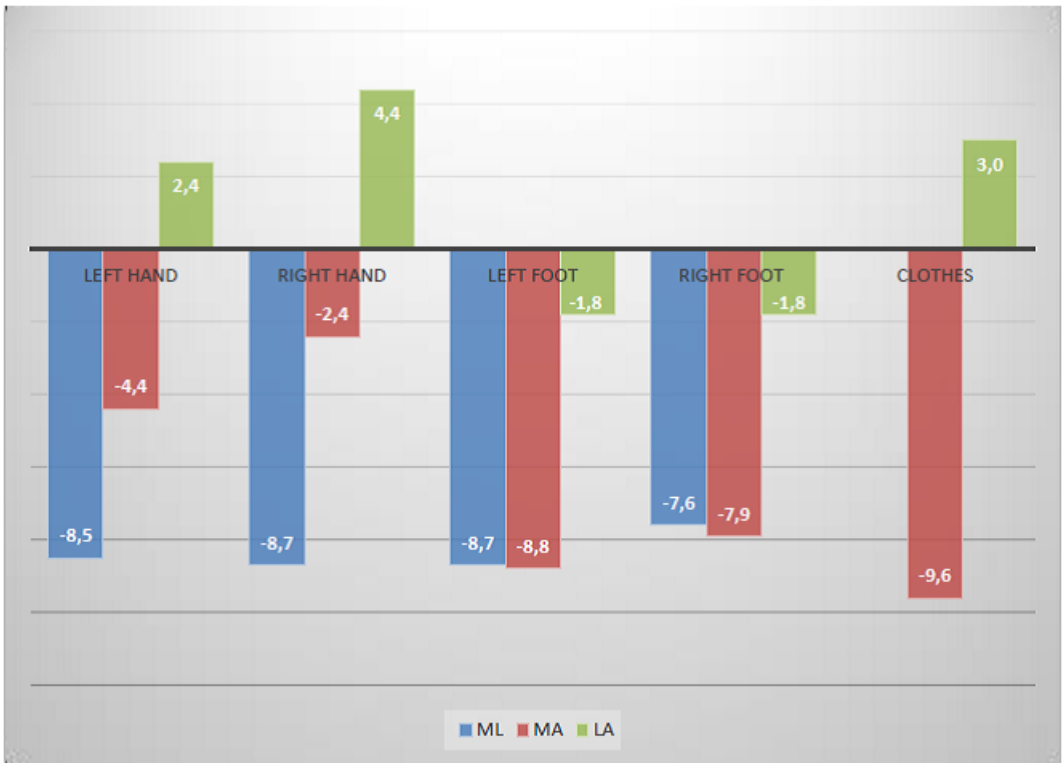

Figure 4.7: Representation of the different proportions after the Benjamini-Hochberg test for time of day. Where ML (Morning and Lunch), MA (Morning and Afternoon) and LA (Lunch and Afternoon).

4.5.3 Contamination per Period

Figure 4.8 summarises the contamination versus period. The first three weeks of taking measurements before the two-week break were called the first period (period 1). This period had high peaks of detected radioactive contamination, which gradually decreased through the third period (period 3). The high detected radioactive contamination in the first period is likely due to participants not being conscious of possible contamination on the hands, feet and clothing. However, it gradually decreased in period 2 and even more in period 3 as the participants anticipated the measurement and probably became more cautious. Although there was an outlier in the third period, it was not as much compared to period one.

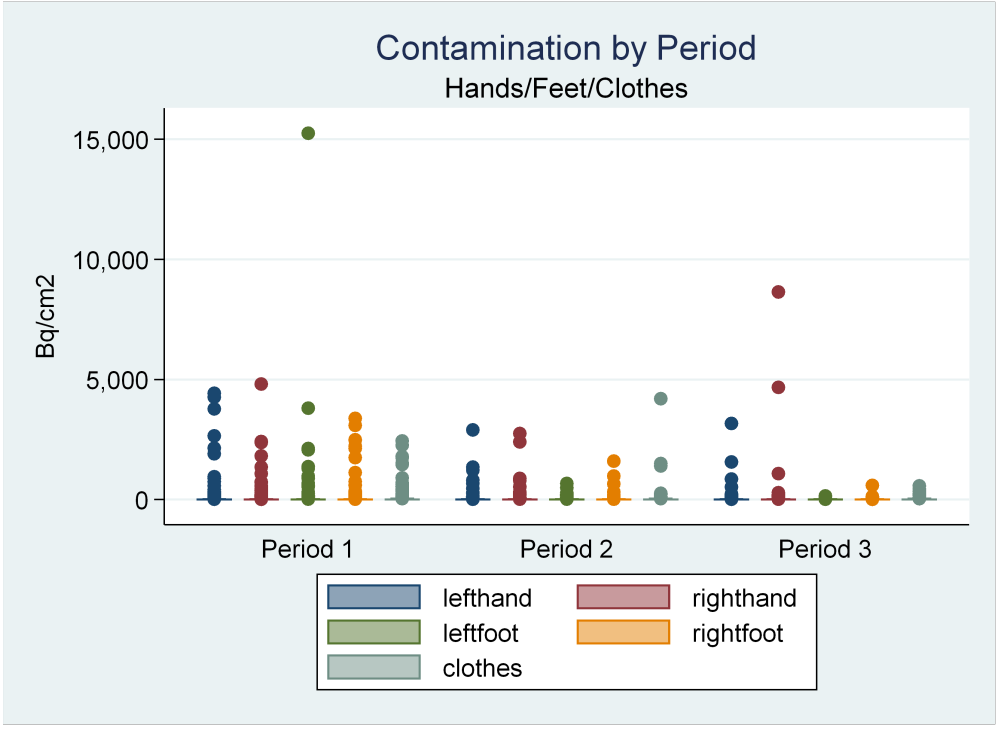

Figure 4.8: Relationship between the detected contamination on hands, feet and clothing for the three periods considered during the study.

The median and IQ range of detected contamination on hands, feet and clothing shown in Table 4.6, after adjustment using the Benjamini-Hochberg test for non-parametric K-Wallis, were within derived limits from Mountford and the Directorate of Radiation Control [14, 16, 13]. The Directorate of Radiation Control in the department of health is responsible for regulating and controlling radioactive products. It is also responsible for authorising, inspecting, reviewing and enforcing compliance [45]. However, the p-values from Table 4.6 are not statistically significant, except for the right hand with a p-value of 0.0033, which may be attributed to the majority of participants being on leave of absence during periods 2 and 3 and some staff having no contamination detected. However, Fig. 4.9 shows the right hand had 3.5 times less difference for radioactive contamination between periods 1 and 2, and 1.9 times less for period 1 compared to period 3. When looking at periods 2 and 3, the proportional difference between the left foot and the right foot is two times more contaminated in period 2 than in period 3. In Fig. 4.9, P1/2 represents periods 1and 2, P1/3 represents periods 1 and 3, and P2/3 represents periods

2 and 3.

Table 4.6: Median and IQ range for detected contamination with period

Rank	Left hand (Bq/cm^2)	Right hand (Bq/cm^2)	Left foot (Bq/cm^2)	Right foot (Bq/cm^2)	Clothes (Bq/cm^2)
Period					
1	3(1-4)	0.7(0-4.9)	0.2(0-7.1)	0(0-5.7)	5.3(0.9-15.2)
2	3(1-4)	1.1(0-4.9)	0.9(0-6.1)	1.2(0-6.9)	6.1(2.6-16.2)
3	3(1-4)	0.1(0-4.6)	0.4(0-5.2)	0(0-4.2)	5.9(2.1-15.2)
p-value	0.1147	0.0033	0.0644	0.0728	0.1232

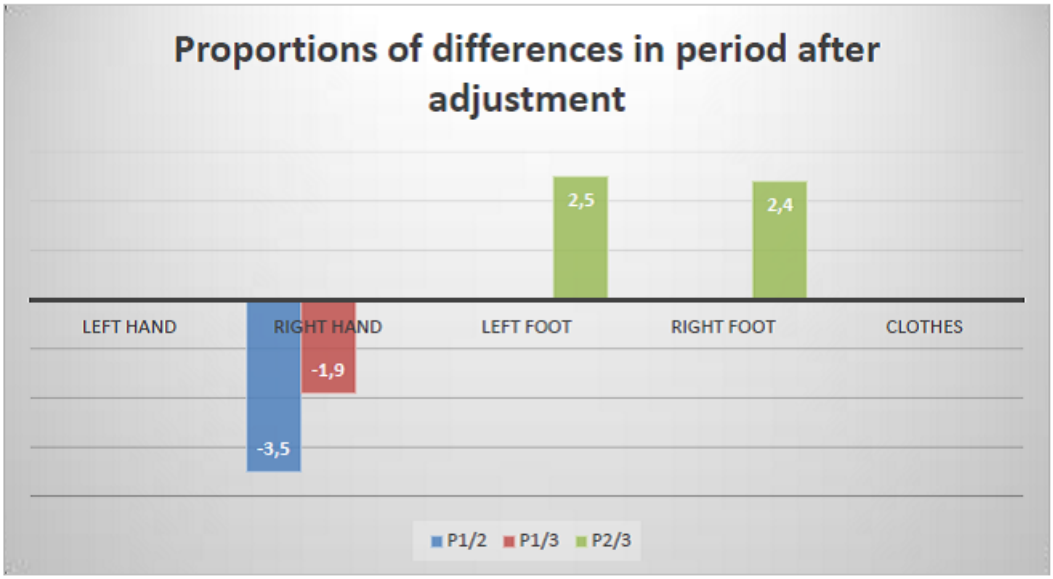

Figure 4.9: different proportions for different period after using Benjamini-Hochberg test

4.5.4 Contamination per location

This section summarises the detected contamination in different locations, as explained in Section 2.4. Contamination levels for different areas within the nuclear medicine department, where the participants were carrying out various tasks, are illustrated in Fig. 4.10. It was found that the gamma camera room

and hot laboratory have the highest radioactive contamination, followed by the Positron Emission Tomography/Computed Tomography (PET/CT) room with its specific hot laboratory. The higher detected contamination in the general hot laboratory results from the numerous radiopharmaceuticals being prepared there. The gamma camera room follows suit due to the number of patients undergoing imaging daily, compared to PET/CT, including its specific hot laboratory.

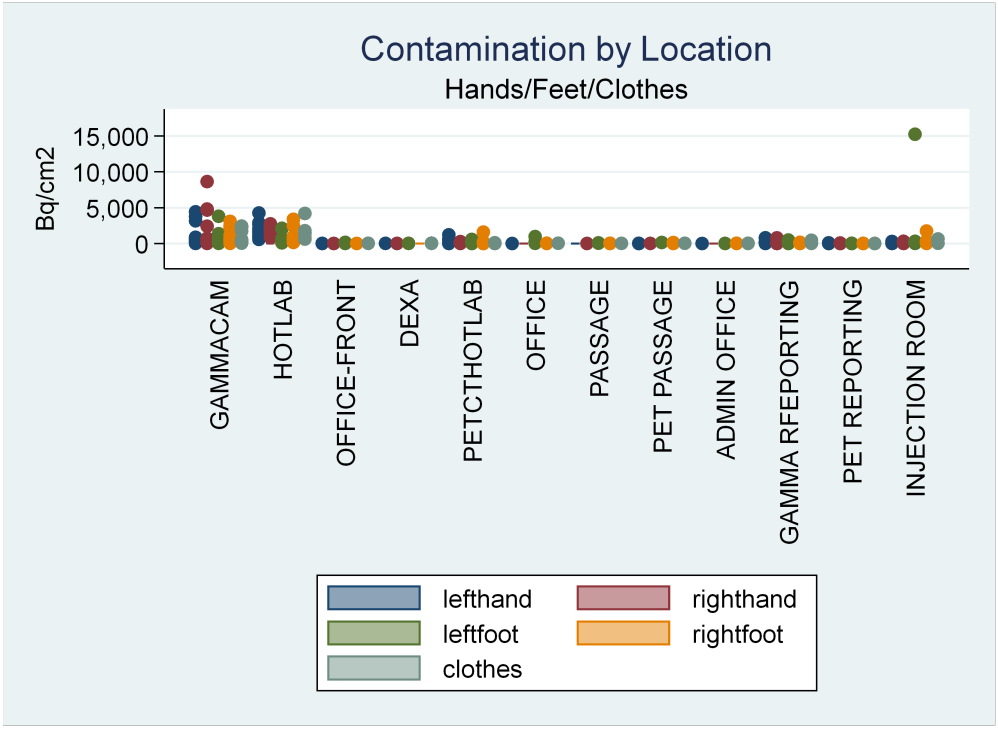

Figure 4.10: Relation between the detected contamination and location

Table 4.7 summarises the detected radioactive contamination after adjustment using the Benjamini-Hochberg test for the non-parametric K-Wallis showing the median and interquartile range. The median and interquartile ranges for different locations were within the allowed surface contamination level, except for the hot laboratory, which had 68 observations. In the hot lab, the third quartile range for the left hand, left foot and right foot were higher than the limits stated by Mountford and Directorate Radiation Control [14, 16, 13]. The median and third quartile for the right hand of personnel in the hot laboratory was 36.7 Bq/cm^2 and 300 Bq/cm^2, and for the hot laboratory, clothes were 44

Bq/cm^2 and 240 Bq/cm^2, respectively. These median and third quartiles were higher than the acceptable radioactive contamination levels [14, 13, 16, 15]. The higher median and third quartile of radioactive contamination could be due to all the radiopharmaceuticals associated with ^{99m}Tc radionuclide prepared here and that most cases in the department use ^{99m}Tc radionuclide. The p-value obtained for location was statistically significant, as shown in Table 4.7. Fig. 4.11 summarises the results after adjustment using the Benjamini-Hochberg to test the difference in significance in different locations. Compared to the clothes in the PET, the clothes in the hot laboratory were 12.3 times more contaminated and considered the highest difference. However, the gamma camera room had the lowest difference of 7.6 less for the right hand compare to the hot laboratory, followed by the PET/CT hot laboratory with a difference of 7.5 less than the gamma injection room for the left foot. In Fig. 4.11, the following abbreviations apply:

- GH - gamma camera and hot laboratory,
- GO - gamma camera and office-front,
- GPH - gamma camera and PETCT hot laboratory,
- GOF - gamma camera and office,
- GPP - gamma camera and PET Passage,
- GA - gamma camera and administrative office,
- GGR - gamma camera and gamma reporting room,
- GPR - gamma camera and PET reporting room,
- GGI - gamma camera and gamma injection room,
- HO - hot laboratory and office-front,
- HD - hot laboratory and dual-energy X-ray absorptiometry (DEXA),
- HPH - hot laboratory and PETCT hot laboratory,
- HOF - hot laboratory and office,
- HPA - hot laboratory and passage,
- HPP hot - and PET passage,

- HA - hot laboratory and administrative office,
- HPR - hot laboratory and gamma reporting room,
- HGI - hot laboratory and gamma injecting room,
- OGR - front office and gamma reporting room,
- OPR - front office and PET reporting room,
- OD - front office and DEXA,
- OPH - front office and PET/CT hot laboratory,
- OPA - front office and passage,
- DPH - DEXA and PETCT hot laboratory,
- DO - DEXA and office,
- DPP - DEXA and PET passage,
- DPR - DEXA and PET reporting room,
- PHO - PETCT hot laboratory and office,
- PHP - PETCT hot laboratory and passage,
- PHPP - PETCT hot laboratory and PET passage,
- PHA - PETCT hot laboratory and administrative office,
- PHGR - PETCT hot laboratory and gamma reporting room,
- PHPR - PETCT hot laboratory and PET reporting room,
- PHGI - PETCT hot laboratory and gamma injection room,
- OP - office and passage,
- OA - office and administrative office,
- OGR - office and gamma reporting room,
- OPR - office and PET reporting room.

Table 4.7: Median and IQ range for detected contamination at different locations

Rank	Left hand (Bq/cm^2)	Right hand (Bq/cm^2)	Left foot (Bq/cm^2)	Right foot (Bq/cm^2)	Clothes (Bq/cm^2)
Location					
Gamma camera (325)	2.1(0-6.7)	0.9(0-7.2)	1.3(0-9.4)	1.2(0-8.7)	9.2(2.6-23.1)
Hot lab (68)	25(6.5-212.5)	36.7(5-300)	5.6(0.45-36.9)	6.9(1-60)	44(6.4-240)
Office front (49)	0(0-2.2)	0(0-3.7)	0(0-4.8)	0.2(0-3.9)	7.9(3.7-11.6)
Dexa (28)	1.9(0-3.8)	0(0-3.5)	0.01(0-6.98)	0.3(0-7.7)	3.5(6.5-12)
Pet CT hot lab (75)	0.2(0-3.7)	0.3(0-3.9)	0.1(0-0.4)	0.1(0-0.5)	0.4(0.1-2.26)
Office(39)	0(0-2.1)	0.9(0-3.9)	1.8(0-4.7)	0(0-4.7)	5.8(2.8-13.9)
Passage(20)	2.3(0.02-5.3)	0.9(0-3.5)	0(0-6.6)	0(0-2.8)	7.7(3-13)
Pet Passage(24)	0(0-0.6)	0.3(0-5.9)	0.5(0-6.8)	0.06(0-5.5)	8.9(1.7-15.6)
Admin office(47)	0(0-2.1)	0(0-3.1)	1.3(0-5.5)	0.1(0-5.1)	3.6(1.1-7.2)
Gamma reporting(206)	1.1(0-4.1)	0.002(0-2.8)	1(0-5.3)	0(0-3.1)	4.7(2.6-11.6)
Pet reporting(86)	0.02(0-0.2)	0(0-0.07)	0(0-0.3)	0(0-0.2)	0.3(0.2-0.6)
Gamma injection room(169)	0.6(0-3.9)	0(0-3.8)	1(0-9.2)	0(0-7.3)	6.9(3.1-15.9)
p-value	0.0001	0.0001	0.0001	0.0001	0.0001

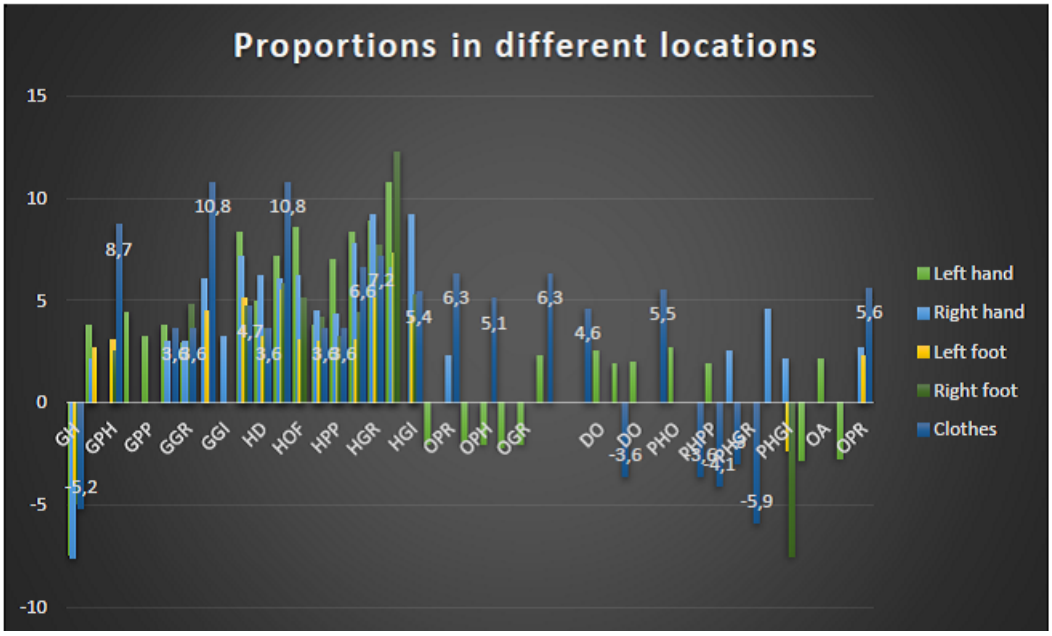

Figure 4.11: Plot of the proportion difference of contamination levels at different locations

4.5.5 Contamination per radionuclide

The detected radioactive contamination for left and right hand, left and right foot and clothing from the different radionuclides ranges from zero to slightly above 15 000 Bq/cm^2,as shown in Fig. 4.12. ^{99m}Tc radionuclide has the highest detected contamination, followed by ^{18}F. The higher contamination detected on the left and right hand, left and right foot and clothing for ^{99m}Tc radionuclide is mainly due to it being the most used nuclide for different patient cases in the department. Another reason is related to the long half-life of ^{99m}Tc compared to ^{18}F that prolongs the radionuclide decay. It could also be due to the established knowledge that the contamination of ^{18}F-FDG on the hands is easily decontaminated. Staff do not need to prepare patient doses because it arrives as an individual patient dose. However, it is not easy to decontaminate ^{99m}Tc-labelled radiopharmaceuticals [18, 46]. It is essential to mention that Fig. 4.12 is similar to the graph in the study done by Covens and colleagues (2012; 2011) [18, 46]. ^{123}I radionuclide has the outlier on the left foot, so the contamination source could be from the contaminated floor. Also,

^{99m}Tc radionuclide had an outlier detected on the right hand, which could have resulted from a spill.

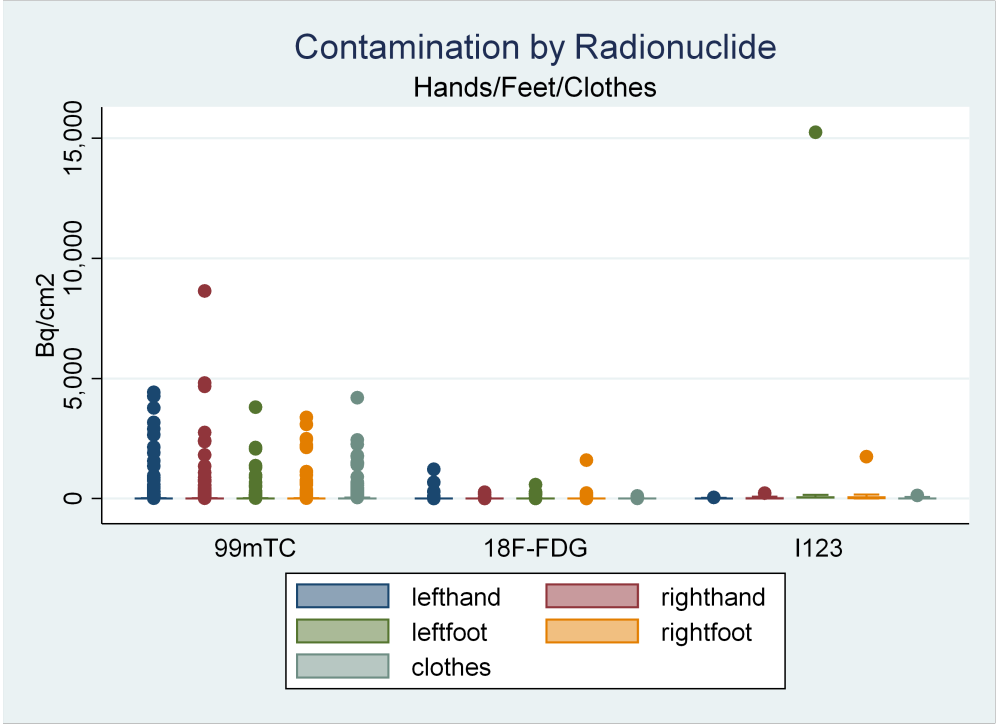

Figure 4.12: Plots of contamination levels detected for different radionuclides ^{99m}Tc, ^{18}F-FDG and ^{123}I

Table 4.8 shows the summary of the detected radioactive contamination after adjustment using the Benjamini-Hochberg test for non-parametric K-Wallis. The p-values in the table were statistically significant. The ^{99m}Tc and ^{18}F radionuclides had a median and IQ range for detected radioactive contamination within the allowed surface contamination limit [14, 16, 13]. However, ^{18}F radionuclide had the lowest median and IQ range, which could be because ^{18}F-FDG doses are not prepared in the nuclear medicine department. The doses come as individual patient doses from South African Nuclear Energy Corporation (NECSA), allowing staff to manipulate the dose to suit specific patients. In our study, ^{123}I radionuclide was not as commonly used as^{99m}Tc and ^{18}F radionuclides. However, it was observed that the third quartile of contamination for the right hand was 65.7 Bq/cm^2, the right foot was 98.1 Bq/cm^2 and 43 Bq/cm^2, which is higher than the derived limit of surface contamination. The

left foot has a high median of 34.2 Bq/cm^2 and a third quartile range of 96.2 Bq/cm^2 above the allowed limits of contamination [14, 16, 13]. Figure 4.13 shows 12 times more contamination on clothes by ^{99m}Tc radionuclide than ^{18}F because ^{99m}Tc has a half-life of 6.6 hrs compared to ^{18}F, which has a half-life of 110 mins. The half-life indicates that ^{99m}Tc takes longer to decay than ^{18}F and is difficult to decontaminate. There was 2.8 times less contamination by ^{18}F found on the right foot and clothes compared to ^{123}I.

Table 4.8: Median and IQ range for detected contamination with radionuclide

Rank	Left hand (Bq/cm^2)	Right hand (Bq/cm^2)	Left foot (Bq/cm^2)	Right foot (Bq/cm^2)	Clothes (Bq/cm^2)
Radionuclide					
^{99m}Tc(917)	1.3(0-5.3)	0.6(0-5.3)	1.2(0-7.3)	0.005(0-6.2)	7.1(2.8-18.4)
^{18}F(183)	0.07(0-0.5)	0.03(0-0.5)	0.04(0-0.4)	0.01(0-0.3)	0.4(0.2-2.6)
^{123}I(8)	2.6(0-17.6)	3.8(0-65.7)	34.2(0-96.2)	10.9(0.1-98.1)	4.7(3.1-43)
p-value	0.0005	0.0051	0.0001	0.0020	0.0001

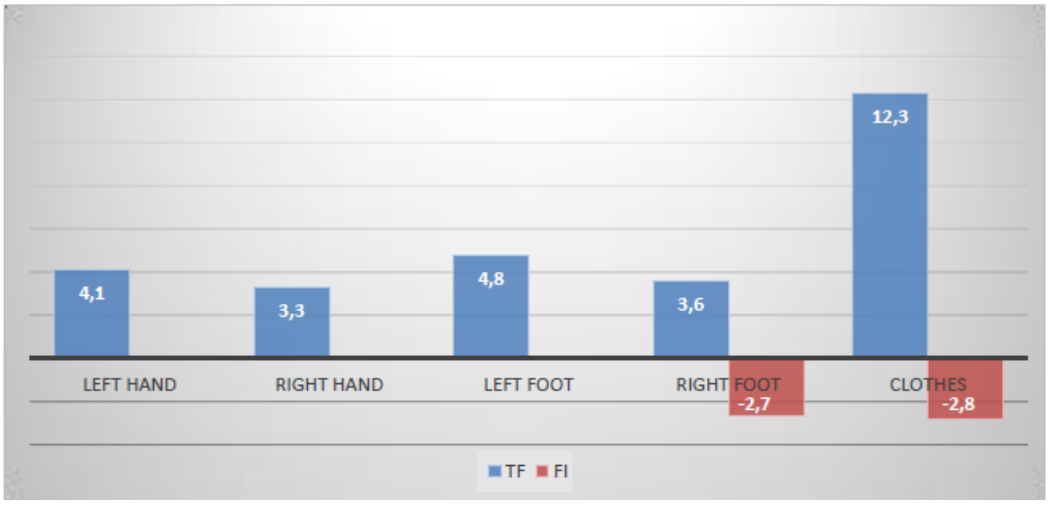

Figure 4.13: Different proportions for different radionuclides considered where TF represents (^{99m}Tc and ^{18}F) and FI represents (^{18}F and ^{123}I)

4.6 Specific detected contamination

Seven specific detected contamination were clarified in this study. The specific detected contamination are: Contamination on an administrator, Contamination on a secretary, Contamination on a medical physicist, Contamination on nurses,Contamination on students, Contamination on doctors, and Contamination on radiographers. The figures in this section are plots of contamination with the code (number) assigned to participant according to their profession. This code was given as a way to protect the participant's identity.

4.6.1 Contamination detected on an administrator

An administrator in the NMD at CMJAH shares an office with radiographers who collect request forms from referral doctors. Figure 4.14 summarises the radioactive contamination detected on the administrative participant. The detected radioactive contamination is within the derived limit for surface contamination, except for the right foot and clothes, which are slightly higher than the limit [14, 16, 13]. The higher contamination of clothes could result from cross-contamination from radiographers due to sharing an office and other equipment such as a printer, computer, and chair.

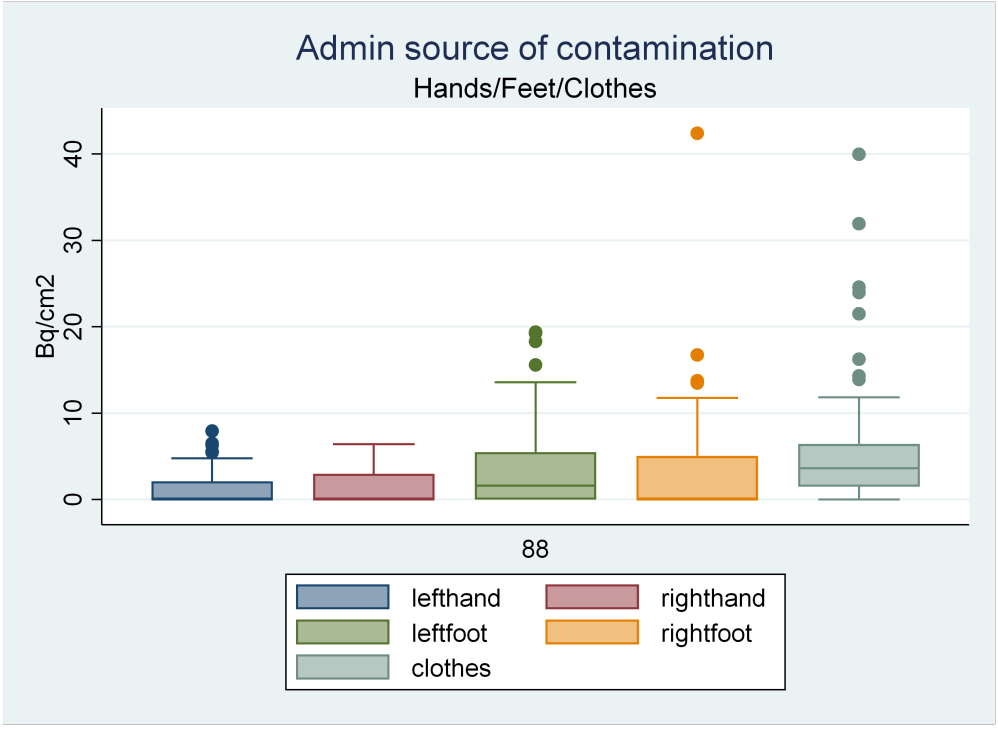

Figure 4.14: Radioactive contamination detected on an administrative staff participant

4.6.2 Contamination detected on a secretary

Figure 4.15 shows the results for the secretary. There was high contamination on the left foot of the secretary, the origin of which is unknown since the secretary spends most of his/her time in an inactive area.

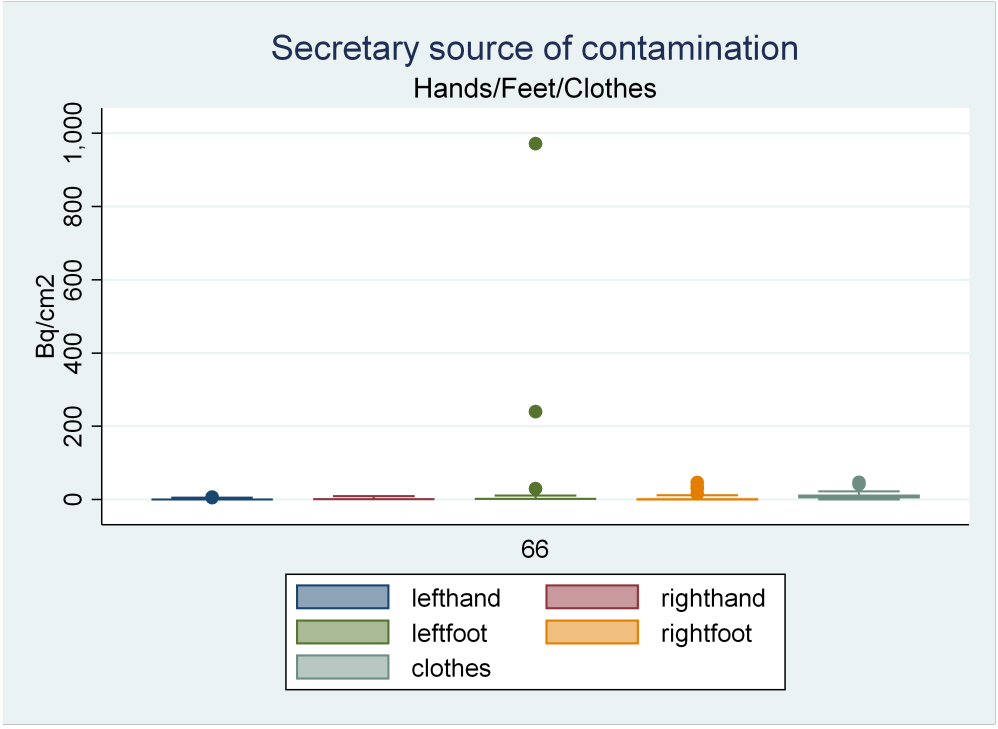

Figure 4.15: Radioactive contamination detected on a secretary

4.6.3 Contamination detected on a medical physicist

The results in Figure 4.16 are for a medical physicist in this study. The results show that the left foot had slightly higher radioactive contamination above the allowed surface contamination limit, yet the right foot was below the permitted contamination limits [14, 16, 13]. The right and left foot could have received this contamination via a minor spill that may have occurred on the department floor. However, hands and clothing had detected radioactive contamination within the derived limits.

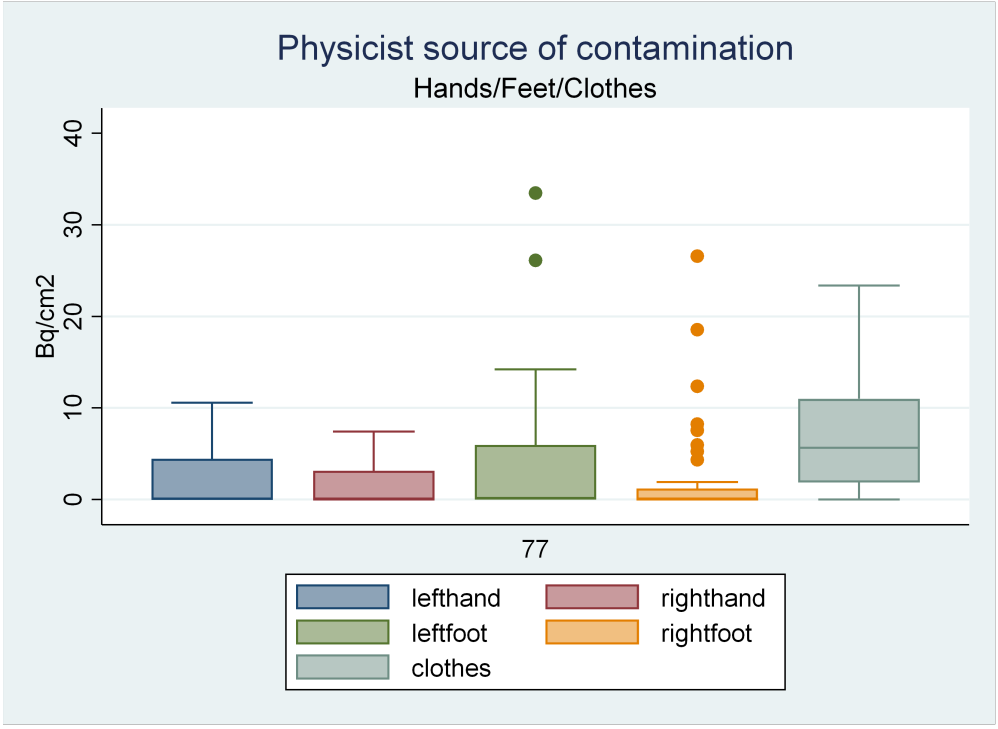

Figure 4.16: Radioactive contamination detected on a medical physicist

4.6.4 Contamination detected on a general assistants

Figure 4.17 shows the summary of detected radioactive contamination on GAs. There were two full-time GAs in the department. Both had high radioactive contamination on their feet, exceeding the derived limit for surface contamination due to contaminated floors in the hot laboratories, injection rooms or both. Their hands and clothing had less contamination, except for one participant's left hand, which was slightly higher than the derived limit for surface contamination [14, 16, 13]. We cannot explain the reason behind that but speculate that the gloves worn while cleaning in the department might have holes.

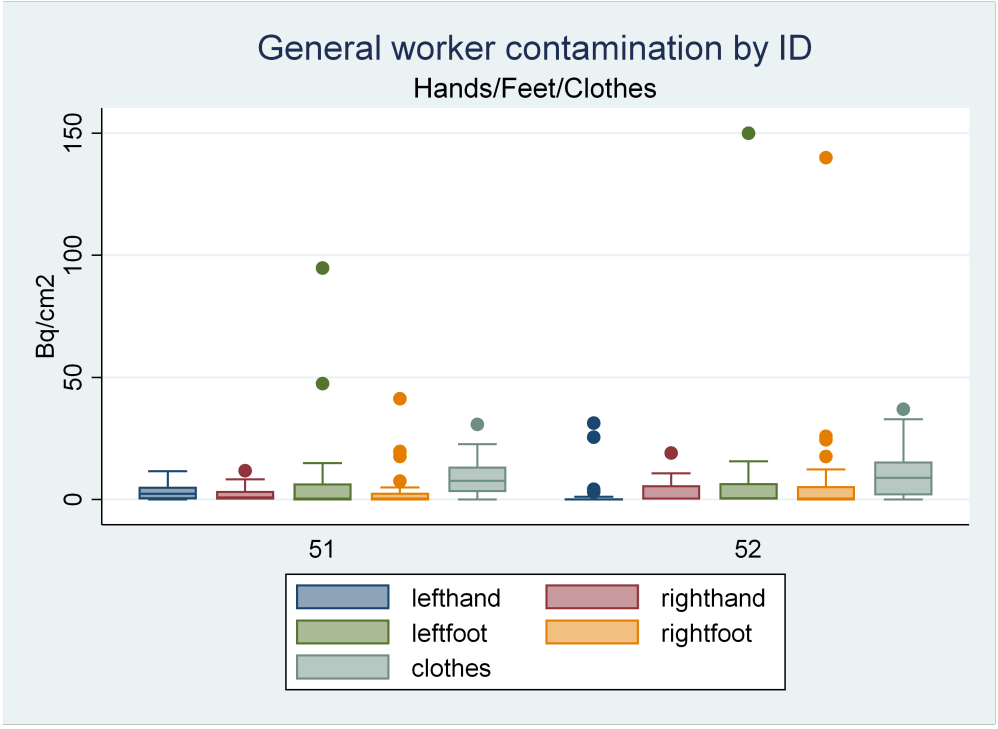

Figure 4.17: Radioactive contamination detected on general workers

4.6.5 Contamination detected on nurses

The radioactive contamination level among the nurses is shown in Fig. 4.18. There were four nurses involved in this study; all of them classified as radiation workers. Classifying them as radiation workers is because they could receive a third of the annual radiation dose. One participant had high radioactive contamination on the left foot, which was also observed in Fig. 4.12 for ^{123}I radionuclides. This may be because there was a minor spill during the preparation of ^{123}I to be injected into a patient and because the floor was contaminated with ^{123}I. This high detected radioactive contamination from one of the nurse could be classified as an outlier and it affects the actual spread of radioactive contamination among nurses in the department.

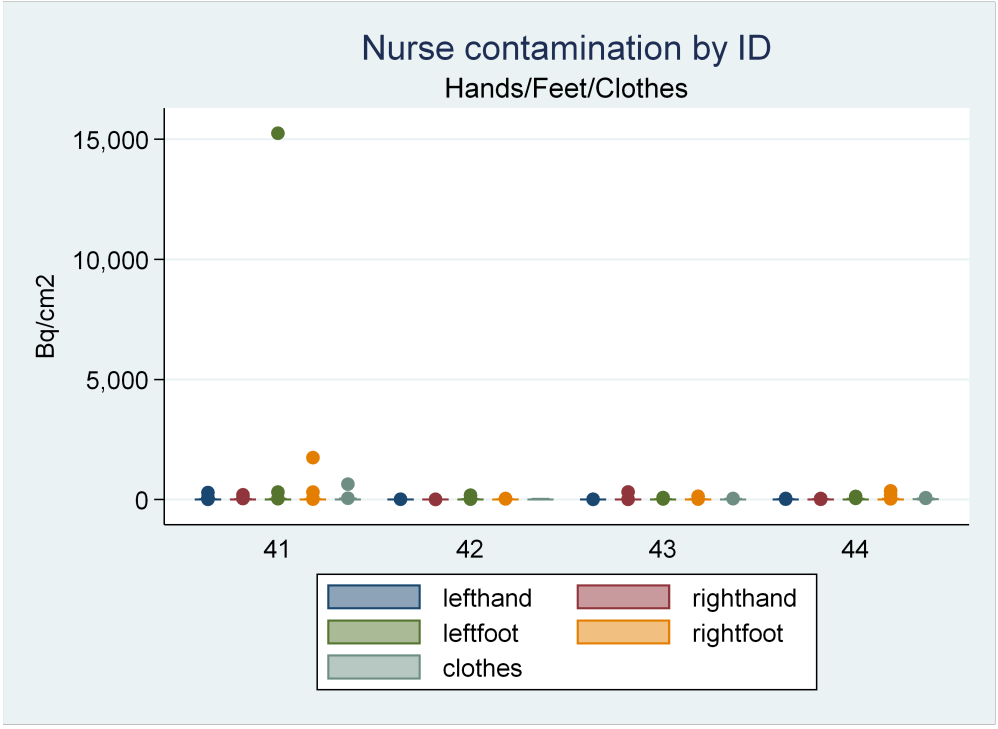

Figure 4.18: Radioactive contamination detected on nurses.

4.6.6 Contamination detected on students

Figure 4.19 results are for students who alternate between different rooms as they are attached to certain radiographers for training. They may be contaminated as they prepare radiopharmaceuticals and position patients on the machines. The hands and clothing of one participant had the highest detected radioactive contamination compared to other students. This may be explained by touching clothes with contaminated hands.

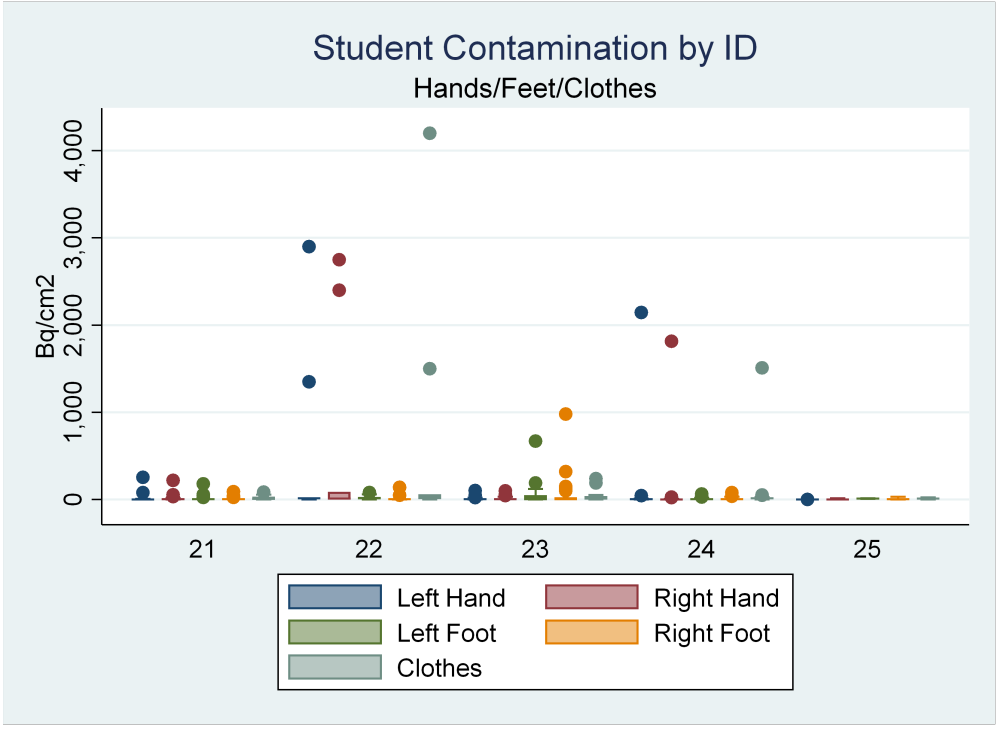

Figure 4.19: Radioactive contamination detected on students.

4.6.7 Contamination detected on doctors

Figure 4.20 shows the results of contamination on the doctors in the department and demonstrate radioactive contamination. The high contamination in one participant may be the results of preparing and injecting ^{123}I radionuclide. The contamination on the feet most likely results from the radioactive material contaminating the floor.

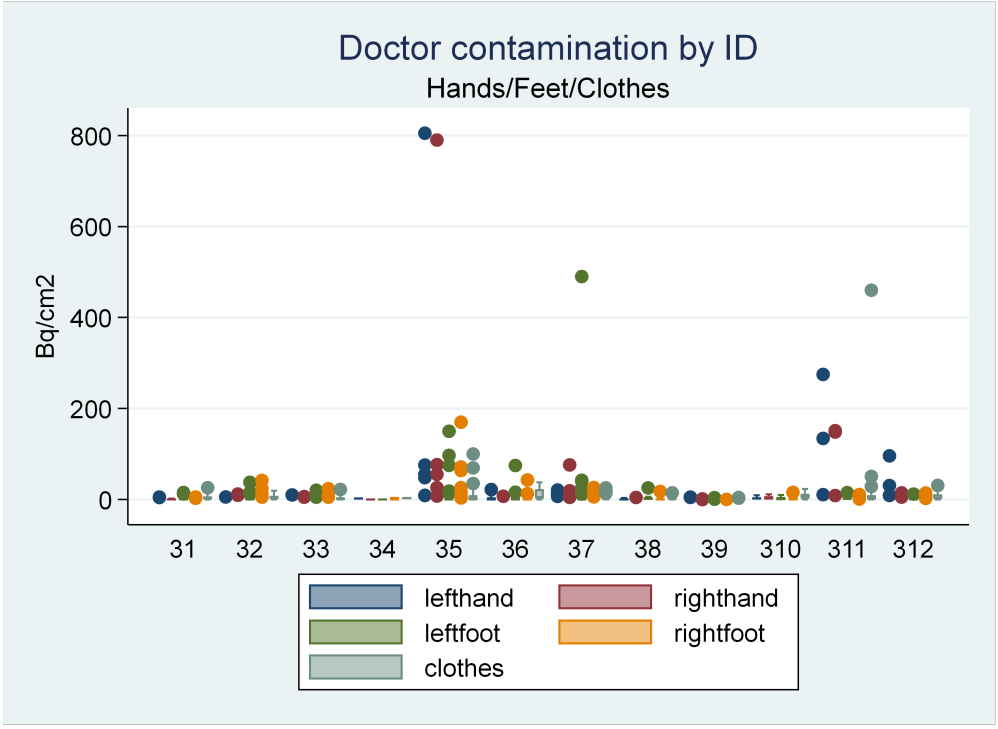

Figure 4.20: Radioactive contamination detected on doctors.

4.6.8 Contamination detected on radiographers

The radiographers' results are summarised in Fig. 4.21. The figure shows the presence of radioactive contamination on the radiographers. Different levels of contamination are shown from different radiographers. This high contamination most likely results from preparing radiopharmaceuticals in the hot laboratory since hands are generally close to the hot area of preparation and the patient's mouth when holding the aerosol delivery tube. High contamination was also observed on the feet, meaning that the floor in the hot laboratory, gamma camera imaging room and PET/CT hot laboratory were contaminated. Clothing was also noted to have high contamination in some radiographers, which could be as a result of spillage or radiographers touching their clothes before decontaminating them.

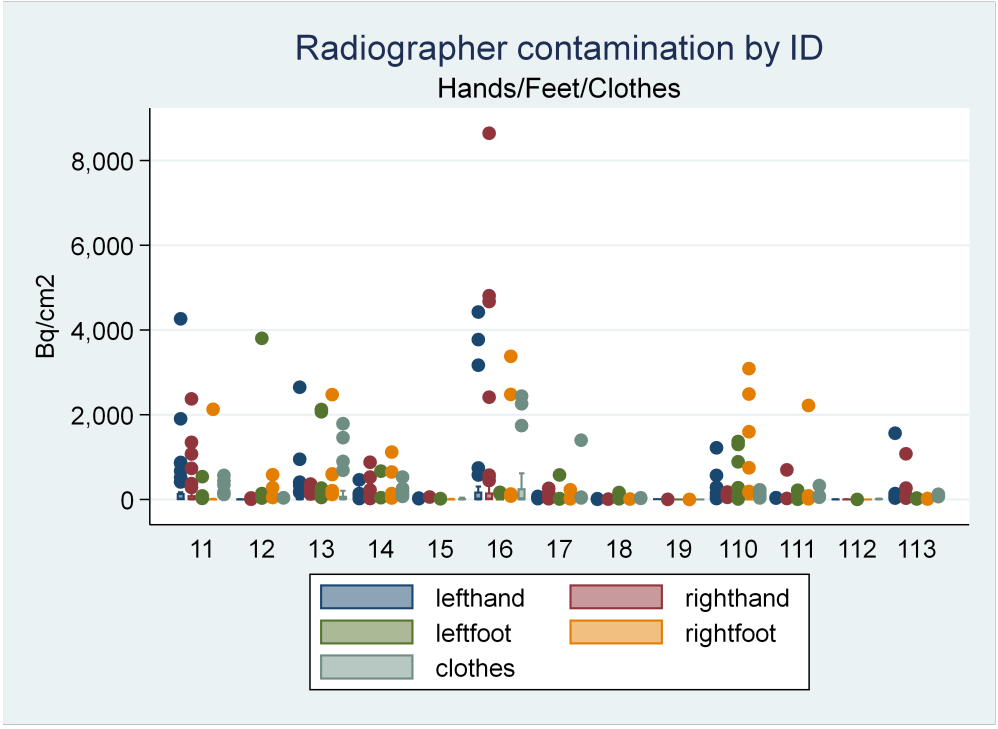

Figure 4.21: Radioactive contamination detected on radiographer.

4.7 Staff radiation dose measured using TLD

Table 4.9 show the summary of radiation dosage monitored in the department for both deep and skin dose. The radiation dose was monitored using the TLD badge from SABS. The results were taken for three months during the period of our study.

Table 4.9: Radiation dose measurement for staff in the Nuclear Medicine Department at CMJAH

	Deep Dose (mSv)	Skin Dose (mSv)
average	0.67	0.77
median	0.36	0.35
IQ range	(0.00-0.96)	(0.00-0.94)
min	0.00	0.00
max	3.01	6.45

The recommended deep dose (effective dose) is 20 mSv per year averaged over five years [9, 47]. The deep dose of 20 mSv per year suggests that in three months, the accumulated dose will be 4.62 mSv. In addition, the recommended skin dose is 500 mSv per year [9, 47]. The skin dose of 500 mSv per year suggests that in three months, the accumulated dose would be 115.38 mSv. The reason for these calculations is because TLD badges from the SABS are changed 13 times per year. The SABS recommends a pro-rata limit of 4 mSv per wearing period [48]. The radiation monitoring results show that the radiation dose in Table 4.9 was much less than the effective dose limits and annual equivalent dose limits for staff in the department. Although high detected radioactive contamination was observed among different professions, the radiation doses from our staff were within the accepted national and international limits [9, 47]. However, the threshold for SABS is too high for this study since they don't record deep dose less than 0.15 mSv and beta skin dose less than 3.25 mSv. This threshold may have an effect on the low contamination, since the exposure may not be recorded although it was registered.

Chapter 5

Conclusion and Recommendations

The study was designed and carried out to assist staff in the NMD at CMJAH, to be aware of radioactive contamination that happens during their duties. Radioactive contamination was found to be present in the department, but approximately 92% was within the derived limit of surface contamination. This research demonstrated that radiographers and student radiographers were more exposed to contamination due to the nature of their profession. Contamination seems to increase with time and becomes more frequent from the middle to the end of the day. ^{99m}Tc radionuclide contributed more to the radioactive contamination due to it being more frequently used. The gamma camera imaging room and hot laboratory are the sites of most exposure.

Limitations of the current study

- One of the study's limitations was finance; we had to compromise and use only the right foot detector to measure the left foot. We could not afford to buy a left foot detector contamination monitor on time.
- The results for hand-foot-clothes contamination were recorded manually. This could affect the data if the researcher was not present to record the detected contamination readings when the monitor was checking the staff.
- The hand-foot-clothes contamination monitor was not located at the

entrance/exit of the department, so some staff would only measure radioactive contamination in the morning and lunchtime.

- The other limitation that also impacted the study is that some of the department staff were on leave of absence during the study period.

Recommendation

- For good practice, staff should only use laboratory coats designated for the hot laboratory and other coats outside the hot laboratory.
- To prevent cross-contamination from hands, the hot laboratory must have a designated pen not removed from the room.
- The contamination monitor must be at the entrance/exit of the department as per standard regulations.
- Radioactive contamination should be checked every morning and before leaving the department or when a person suspects contamination. If radioactive contamination is found, the person must decontaminate themselves as soon as possible to minimise radiation exposure.
- For good practice, an administrator should not share an office and other equipment such as a printer, computer and chair.
- Gloves should always be worn when working with radiopharmaceuticals and hands washed immediately after removing the gloves.

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Appendix A

R14/49 Prof Mboyo Di Tamba Willy Vangu and Mr P. Sithole

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M170203

NAME: (Principal Investigator)	Prof Mboyo Di Tamba Willy Vangu and Mr P. Sithole
DEPARTMENT:	Radiation Sciences/Nuclear Medicine/Medical Physics Charlotte Maxeke Johannesburg Academic Hospital
PROJECT TITLE:	Hand-Foot-Clothes Contamination in Nuclear Medicine: Monitoring of Staff at Charlotte Maxeke Johannesburg Academic Hospital
DATE CONSIDERED:	24/02/2017
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	
APPROVED BY:	Professor P. Cleaton-Jones, Chairperson, HREC (Medical)
DATE OF APPROVAL:	10/04/2017

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary in Room 10004,10th floor, Senate House/2nd floor, Phillip Tobias Building, Parktown, University of the Witwatersrand. I/We fully understand the the conditions under which I am/we are authorised to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit to the Committee. **I agree to submit a yearly progress report**. The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. in this case, the study was initially review in February and will therefore be due in the month of February each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

Figure A.1: Ethics Clearance Certificate

Appendix B

Table B.1: After correction with Benjamin-Hocherberg test the areas of significance and level mentioned below

	Radiographer	Student	DR	Nurse
DR				
Left hand	5.5	4.1		
Right hand	6.6	4.7		
Left foot	2.7	5.2		
Right foot	6.1	6.1		
Clothes	6.5	6.6		
Nurse				
Left hand	3.7	3.2		
Right hand	4.4	3.6		
Left foot		3.3		
Right foot				
Clothes		2.4		
GW				
Left hand	2.5	2.7		
Right hand				
Left foot		2.9		
Right foot		3.1		
Clothes		2.3		
Secretary				
Left hand	4.7	4.6	2.2	2.5
Right hand		2.2		
Left foot		2.5		
Right foot	2.3	3.6		
Clothes		2.4		
Physicist				
Left hand	2.3	2.5		
Right hand	2.6	2.8		
Left foot		3		
Right foot	3.4	4.6		2.6
Clothes		3.4		
Admin				
Left hand	4	4		
Right hand	3.6	3.6		
Left foot		2.2		
Right foot		2.9		
Clothes	2.9	4.4		2.9

Table B.2: time of the day

	Morning	Lunch
Lunch		
Left hand	-8.5	
Right hand	-8.7	
Left foot	-8.7	
Right foot	-7.6	
Clothes		
Afternoon		
Left hand	-4.4	2.4
Right hand	-2.4	4.4
Left foot	-8.8	-1.8
Right foot	-7.9	-1.8
Clothes	-9.6	3

Table B.3: Different Period

	Period 1	Period 2	Period 3
Period 2			
Left hand			
Right hand	-3.5		
Left foot			
Right foot			
Clothes			
Period 3			
Left hand			
Right hand	-1.9		
Left foot		2.5	
Right foot		2.4	
Clothes			

Table B.4: Different location

	Gamma cam	Hot lab	Office	Dexa	Pet hot	Office
Hot lab						
Left hand	-7.4					
Right hand	-7.6					
Left foot		-3.9				
Right foot	-4.9					
Clothes	-5.2					
Office						
Left hand	3.8	8.3				
Right hand	2.1	7.2				
Left foot	2.7	5.1				
Right foot		4.7				
Clothes		4.7				
Dexa						
Left hand		5	-1.9			
Right hand		6.2				
Left foot			3.2			
Right foot		3.6				
Clothes		3.6				
Pet hot lab						
Left hand		7.2	-2			
Right hand		6.1				
Left foot	3.1	5.5				
Right foot	2.5	5.8				
Clothes	8.7	10.8	5.1	4.6		
Office						
Left hand	4.4	8.6		2.5	2.7	
Right hand		6.2				
Left foot			3.1			
Right foot		5.1				
Clothes						
Passage						
Left hand		3.8	-2.2			-2.8
Right hand	4.5					
Left foot			3			
Right foot		4.2				
Clothes		3.6			-3.6	
Pet passage						
Left hand	3.2	7		1.9	1.9	
Right hand		4.3				
Left foot			2.7			
Right foot		3.2				
Clothes		3.6		-3.6	-4.1	
Admin office						
Left hand	3.8	8.3		2		2.1
Right hand	3	7.8			2.5	
Left foot		3.1				
Right foot		4.4				
Clothes	3.6	6.6			-3	
Gamma reporting						
Left hand	2.9	8.9	-2			-2.7
Right hand	3	9.2				
Left foot			5.1			
Right foot	4.8	7.7				
Clothes	3.6	7.2			-5.9	
Pet reporting						
Left hand						
Right hand	6.1	10.8	2.3		4.6	2.7
Left foot		4.5	6.6			2.3
Right foot		7.3				
Clothes	10.8	12.3	6.3	5.5		5.6
gamma injection room						
Left hand						
Right hand	3.2	9.2			2.1	
Left foot			4.2		-2.3	
Right foot		5.3			-7.5	
Clothes		5.4				

Table B.5: Radionuclide

	^{99m}Tc(917)	^{18}F-FDG(183)
^{18}F-FDG		
Left hand	4.1	
Right hand	3.3	
Left foot	4.8	
Right foot	3.6	
Clothes	12.3	
Dexa (^{99m}Tc)		
Left hand		
Right hand		
Left foot		
Right foot		
Clothes		-4.9
^{123}I		
Left hand		
Right hand		
Left foot		
Right foot		-2.7
Clothes		-2.8

Appendix C

Staff members Consent will be explain verbally

STUDY TITLE: Hand-foot-clothes contamination in nuclear medicine: Monitoring of staff at Charlotte Maxeke Johannesburg Academic Hospital (CMJAH)

The aims and procedures of this study will be explained to all staff and a cop will be given of an aim and a procedure on request. I have had and understood the explanation of the research.

I have had the opportunity to ask questions and to consider the answers given to me.

I understand that participation in this study is voluntary, that I may decline my consent and if I choose not to participate my decision will not affect my job in the hospital.

I hereby willingly give my informed consent to taking part in this research study.

NAME OF STAFF:

DATE:

SIGNATURE:

I confirm that I have fully explained the nature of the study and the procedure to be followed on the above staff or colleague.

NAME:

DATE:

SIGNATURE:

Appendix D

Table D.1: Dose limits [47]

Dose limit	**Effective dose**	**Equivalent dose**
Occupational dose limit	20 mSv per year, averaged over defined periods of 5 years	20 mSv per year to lens of the eye) 500 mSv per year Skin, Hands and feet
Public	1 mSv in a year	15 mSv per year to lens of the eye 50mSv per year skin Non for hands and feet
Fetus or embryo	1 mSv for the duration of the pregnancy	non