PERFORMANCE EVALUATION AND CROSS-CALIBRATION OF CAPINTEC® CRC 15R AND COMECER DOSE CALIBRATORS

Presented to

DEPARTMENT OF MEDICAL PHYSICS

SCHOOL OF NUCLEAR AND ALLIED SCIENCES

UNIVERSITY OF GHANA

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF

A

MASTER OF PHILOSOPHY

IN

MEDICAL PHYSICS

JULY, 2018

DECLARATION

This thesis is the result of research work undertaken by Mr. ELIAS MWAPE in the Department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. A.K Kyere, Dr. F. Hasford and Dr. E.K. Sosu.

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

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DEDICATION

This research work is dedicated to my lovely fiancée Violet Mbwili for the love, moral and spiritual support. It is also dedicated to my parents Brendah Kasali and Everisto Mwape for making me see the value of education. Last but not the least, dedicated also to all my friends and family especially Bishop Justine Gondwe and the Macedonia church family.

ACKNOWLEDGEMENTS

First and foremost I give Glory, honor and adoration to God Almighty for His grace, guidance and protection throughout the course of this research study. Indeed he has being my strength and shield.

I am also forever indebted to the dedicated team of supervisors Professor A.W.K. Kyere, Dr. Francis Hasford and Dr. Edem Sosu for their invaluable guidance and support rendered to me in seeing this research work to completion.

Special thanks goes to my sponsor, IAEA for the financial support without which this work could not have come to a successful end.

I would also like to thank all my lecturers from the Graduate School of Nuclear and Allied Sciences (SNAS) for the coursework which gave me better foundation for understanding this research work.

I am also grateful to the nuclear medicine department at Korle-Bu Teaching Hospital for allowing to me to use the equipment and materials in the Department. Special thanks more especially to the nuclear medicine technologists Mr. Daniel Ashley and Mr. Adu Asimeng Sarkodie for their cooperation and support throughout the process of data collection.

Special thanks to the entire Nuclear medicine unit at the University Teaching Hospital in Zambia for the encouragement and support throughout my stay in Ghana.

Finally, special thanks to my friends Clement Dominic Chaphuka, Joana Otoo and Silas Chabi for their moral support and encouragements. God richly bless you all.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

^{99m}**Tc**	Technetium 99m
Cs-**137**	Cesium 137
eV	Electron volt
GBq	Gigabequerel
KeV	Kiloelectron volt
mCi	Millicurie
MBq	Megabequerel
AAPM	American Association of Physicists in Medicine
ANSI	American National Standards Institute
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology
NPL	National Physical Laboratory
QA	Quality Assurance
QC	Quality Control

ABSTRACT

Dose calibrators are used for accurate measurement of radionuclide activity which is required to achieve the desired efficacy for the best clinical outcome. Observations from assayed activity with Capintec and Comecer dose calibrators at the nuclear medicine department of the Korle-Bu Teaching Hospital have indicated that the two systems report significantly different (>10%) readings for the same activity source. Also unusually high background readings (>20% of the mean) have been noted at the ^{137}Cs and ^{99m}Tc radionuclide settings for Capintec. The study therefore investigated the reasons for these observations so as to cross-calibrate the two systems to enable accurate measurements of radionuclide sources. Constancy check with ^{137}Cs standard radionuclide source found Comecer and Capintec systems to have standard deviations of 1.2% and 0.74% respectively.The study also revealed deviations within ±5% tolerance for relative response to ^{137}Cs standards at clinically significat radionuclide settings for both systems. The results for accuracy in the measurement of ^{137}Cs standards for Comecer and Capintec systems were found to be 185.1 µCi ±1.4% and 193.7 µCi ±3.1% respectivey. Using constant activity method, both vial and syringe geometry testing yielded uncertainties within ±2% tolerance for both systems. Linearity response for both systems yielded deviations within ±5% tolerance.

However, the study revealed underestimation with Comecer and overestimation with Capintec for ^{99m}Tc assays below 1 mCi by 13-16% and 11-31% respectively. The study also found evidence of residual contamination for Capintec systems within tolerance levels. A calibration curve was developed to determine theoretical activities of ^{99m}Tc on Capintec with Comecer as the reference dose calibrator and the results gave assay accuracy within ±5% tolerance levels. Investigation of the influence of

dial values supplied by Capintec on the measured activity readings on their system found drifts in the gain settings to be the reason for higher measurement readings as compared to Comecer system. However, new dial values were theoretically determined and the gain setting was adjusted to give assay accuracy within ±5% tolerance for ^{99m}Tc and ^{137}Cs sources. Performance evaluation and cross-calibration have been done on Capintec and Comecer dose calibrators. The study revealed variations in the performance of both systems within tolerance levels recommended by standard protocols using appropriate settings and procedures (AAPM Report 181, 2012, IAEA TRS 454, 2006, ANSI N42.13 2004, and IAEA-TECDOC-602, 1991).

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Nuclear medicine is the branch of medical imaging that uses small amounts of radioactive materials for diagnosis, staging of disease, therapy and monitoring the response of a disease process (Bailey et al, 2014). The tracer principle is used in nuclear medicine because of its ability to utilize small amounts of radioactive substance in living organisms without significant pharmacological effect on the body. The practice of nuclear medicine involves administering small amounts of radio-labeled compounds called radiopharmaceuticals. The radiopharmaceutical administered to the patient orally, intravenously or by inhaling localizes in the target cell for either diagnostic or therapeutic purposes. Diagnostic radiopharmaceuticals yield information about where they are localized which can help imaging of the organ of interest in patient using special gamma cameras such single photon emission tomography (SPECT) or positron emission tomography (PET) imaging system. On the other hand, therapeutic compounds target specific tumors, such as thyroid, lymphomas or bone metastases, delivering radiation to tumorous lesions for the purpose of curing, destroying, mitigating or controlling the disease (Bailey et al, 2014 and Cherry et al, 2012).

The activity of a radiopharmaceutical is accurately assayed with the use of a dose calibrator (radionuclide dose calibrator). The accuracy of measurements should be covered by consistent quality control of the instrument, including a daily constancy test, a quarterly linearity test, an annual accuracy check and periodic reassessment of its calibration, traceable to secondary standards (IAEA TRS 454, 2006).

Tyler and Woods (2003) report that it is a good practice to re-measure syringe activity while taking into account geometry dependence so as to administer the correct activity to patients. To reduce the error due this geometry, volume correction factors have to be derived for several medically important radionuclides.

Clinically, a lower than actual activity implies that, the patient will be given a higher than prescribed dosage activity being unnecessarily burdened with extra radiation. On the other hand, a higher dosage of administered activity will be inadequate, demanding repetition of the process which implies extra dose to the patient and occupationally exposed staff. Quality control is therefore critical if the dose calibrator is to be used effectively. A nuclear medicine facility should therefore ensure dose calibrators are regularly checked for any calibration errors to ensure that assay errors of prescribed dosage fall within recommended limits (Khan et al, 2016).

The International Atomic Energy Agency (IAEA) recommends an assay accuracy of ±5% while the American National Standards Institute (ANSI) recommends ±10% assay accuracy for a radionuclide dose calibrator. In most countries, the limit is for a given dose to fall within ±10% of the prescribed dosage (IAEA TRS 454, 2006 and ANSI N42.13, 2004).

1.2 STATEMENT OF THE PROBLEM

Accurate measurement of radionuclide activity is required to achieve the desired efficacy and for the best clinical outcome. Although some manufacturers of the dose calibrators claim high accuracy and reproducibility for the radioactivity measurements, yet few studies have reported variations in these parameters (Sharma et al, 2015).

Bailey et al (2014) reports errors ranging from 64 to 144% of the expected activity using calibration factors supplied by manufacturers of radionuclide dose calibrators. This re-emphasized the need for consistent quality assurance programme to confirm calibrations within a Nuclear Medicine unit.

Other researchers have reported differences in assayed activity for VDR-15R and CAPINTEC CRC®-25R calibrators within ± 10% tolerance as required by well-established international standards. To maintain the effective use and proper function of the dose calibrator, a further evaluation criterion was recommended to include a daily constancy check, an annual accuracy check and a quarterly linearity test (Assan et al, 2012 and IAEA TRS 454, 2006).

The nuclear medicine department of the Korle-Bu Teaching Hospital has Capintec CRC®-15R and Comecer radionuclide dose calibrators. Observations from assayed activity have indicated that the two systems report significantly different (>10%) measurement readings for the same activity source. This study therefore seeks to investigate the reasons for these observations so as to cross calibrate the two systems to enable accurate measurements from any of them. The overall performance of the two systems will also be assessed and evaluated through accuracy, constancy, geometry and linearity quality control tests.

1.3 OBJECTIVES OF THE STUDY

The principal objective of the study is to cross calibrate CAPINTEC ® CRC 15R and COMECER dose calibrators in use at the Nuclear Medicine Department of Korle-Bu Teaching Hospital. The specific objectives are:

1. To assess the performance of Capintec and Comecer dose calibrators.
2. To establish calibration factors for accurate measurement of radionuclide activity on the two systems.
3. To re-calculate dial values for some clinically significant and available radionuclides.

1.4 RELEVANCE AND JUSTIFICATION

Dose calibrators are very important in the practice of nuclear medicine. Their proper use requires a comprehensive quality assurance program to assure the nuclear medicine practitioner that the doses of radioactive materials being administered to the patients are sufficient for the task and do not harm the patient. It is in light of this that the work undertaken in this thesis is important. It is an attempt to evaluate the performance of dose calibrators in the Nuclear Medicine Unit of Korle Bu Teaching Hospital, especially in the absence of a rigorous programme of maintenance and calibration of such equipment in the country.

Results from the comprehensive quality control tests on Capintec and Comecer radionuclide dose calibrators will serve as an integral component of a quality assurance programme at the nuclear medicine department of the Hospital. The study will provide specifically derived calibration and volume correction factors which would be used for future reference by nuclear medicine personnel. The calibration

curve/equation from cross calibration between the two systems will be available to help provide a means of ensuring the correct activity is administered to patients even in the case where one of the radionuclide dose calibrators develops a fault. The cross-calibration will in itself be a quality control measure and serve as double check on radionuclide activity to be administered. Finally, results and recommendations from the study will be valuable to the Nuclear Regulatory Authority for quality assurance audits and also serve as benchmark for further research.

1.5 SCOPE AND DELIMITATION

The research was done at the nuclear medicine department of the Korle-Bu Teaching Hospital in Accra within the period September 2017 to July 2018. The study covers general QC tests (accuracy, constancy, linearity and geometry) performed on Capintec and Comecer dose calibrators. The research also investigated the influence of predetermined dial values on the assay accuracy of Capintec radionuclide dose calibrator.

1.6 ORGANISATION OF THESIS

The thesis consists of a chronological order of five chapters. Chapter one describes the general background to the research, provides an overview of the existing state of knowledge relevant to the study and gives the organization of the thesis. The literature relevant to the research problem is reviewed in chapter two. Chapter three focuses on the materials and methodology of the study. The results obtained are presented and discussed in chapter four. Chapter five covers the conclusions and recommendations from the study. The references section contains citations of other researches and papers relevant to the study. An appendix section is also given for details on the data collected.

CHAPTER TWO

LITERATURE REVIEW

2.1 BASIC PHYSICS OF THE DOSE CALIBRATOR

2.1.1 Radioactive decay

Radioactive decay is the process in which an unstable nucleus releases matter and/or energy during a transition to a more stable form. It may do so by releasing sub-atomic particles and energy, or by capturing an orbital electron into its nucleus thus releasing energy. Atoms that are unstable are also known as radioactive atoms, or radionuclides. The original, radioactive atom is known as the parent. The new nucleus (after decay) is known as the daughter radionuclide. The activity of a radioactive source is the number of disintegrations per second. The SI unit of activity or decay rate is the Becquerel (Bq). The Curie (Ci) is the traditional unit for radioactivity and it approximates the disintegration given out every second by 1g of radium in a state of equilibrium with daughter nuclei (Maher et al, 2006).

$$1Ci = 3.7 \times 10^{10} Bq$$

$$1Bq = 1ds^{-1}$$

Although radioactivity is a random and spontaneous process each radionuclide decays at its rate, having its own decay constant (λ).

$$-\frac{dN}{dt} = \lambda N \qquad (2.1.1)$$

The negative sign shows that the number of nuclei N decreases as time elapses. The activity of a radioactive source A is given by the quantity λN .

The strength of a radioactive source is therefore given by its activity. The solution to first order equation (2.1.1) above is the following function:

$$N(t) = N_0 e^{-\lambda t} \qquad (2.1.2)$$

Where, $N(t)$ is the number of nuclei present at time t and N_0 is the initial number of nuclei at t_0 respectively. From above, the activity can therefore be written as

$$A(t) = A_0 e^{-\lambda t} \qquad (2.1.3)$$

Where, $A(t)$ is the activity at time t and A_0 is the initial activity at t_0 respectively. The process of decay is random for individual atoms. Although the exact moment of an individual atomic decay cannot be predicted, the probability of decay during a given time period can be measured (based on observations from a large number of atoms). The decay constant (λ) is expressed in units of probability per unit time (Cherry et al, 2012 and Maher et al, 2006).

The half-life $T_{\frac{1}{2}}$ is the time required for 50% of the parent atoms to undergo radioactive decay. Substituting $t = T_{\frac{1}{2}}$ and $N(t) = 0.5N_0$ into (2.1.2) gives the relation between the half-life and decay constant (λ):

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \tau \ln 2 \qquad (2.1.4)$$

Where τ is the mean lifetime, defined as the time taken for the nuclei to decay to $\frac{1}{e} N_0$. Also substituting (2.1.4) into (2.1.3) yields;

$$A(t) = A_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{\frac{1}{2}}}} = A_0 \left(\frac{1}{2}\right)^n \qquad (2.1.5)$$

Where n is the number of half-lives.

2.2 INTERACTION OF RADIATION WITH MATTER

Ionizing radiation can be classified into either particulate type (α particle, β particle, etc.), or non-particulate type, such as high-frequency electromagnetic radiation (e.g., γ rays, X-rays, etc.), and both kinds are ionizing radiations. As shown in Figure 2.1, the mechanism of interaction of the two types of radiations with matter is different and forms the basis on which activity is measured (Cherry et al, 2012 and Maher et al, 2006).

2.2.1 Charged particle interaction with matter

Alpha-particle radiation (α-particle): Alpha radiation is identical to a helium nucleus (^4_2He). The α-particle is positively charged (+2e) heavy nucleus, with short range in air, has low penetration and mostly emitted by a radionuclide with energy less than 10MeV. The low penetration makes the α-particle hard to detect. All α-decays go with the emission of photon radiation as the daughter nucleus de-excites. It is this emitted photon that makes it possible to measure activity of a nuclide (Cherry et al, 2012).

β+ Radiation ((positron):β+ particle originates from the nucleus of an atom when a nucleus has too few neutrons relative to protons. A proton is converted into a neutron while releasing a β+ particle is emitted along with some energy. it loses its kinetic energy mainly through direct-ionization and then annihilates with its anti-particle (electron) to produce two 511keV photons in opposite directions (almost at 180^0 with

each other). These photons associated with β+ decay makes it easy to detect β+ radiation .β+ decay is also associated with de-excitation photons (Powsner et al, 2013 and Cherry et al, 2012).

β- Radiation*:* a *β*-particle is a fast moving electron**.** This electron is ejected from the nucleus and mainly loses its kinetic energy by direct ionization. The range of most emitted β's is short. It should be noted that in β+ and β-emission, the emitted electron or positron has a continuous energy spectrum, which ranges from the maximum transition energy E_{max} to zero. β-radiation (except a few high energy βs) is easily stopped in a material. As shown in Figure 2.1, the electron loses energy and continuous low energy photons are emitted. The emission is referred to as Bremsstrahlung. Many radionuclides that decay by β emission also emit de-excitation photons (x-rays, γ-rays), which can be detected to measure the activity of a sample (Powsner et al, 2013 and Cherry et al, 2012).

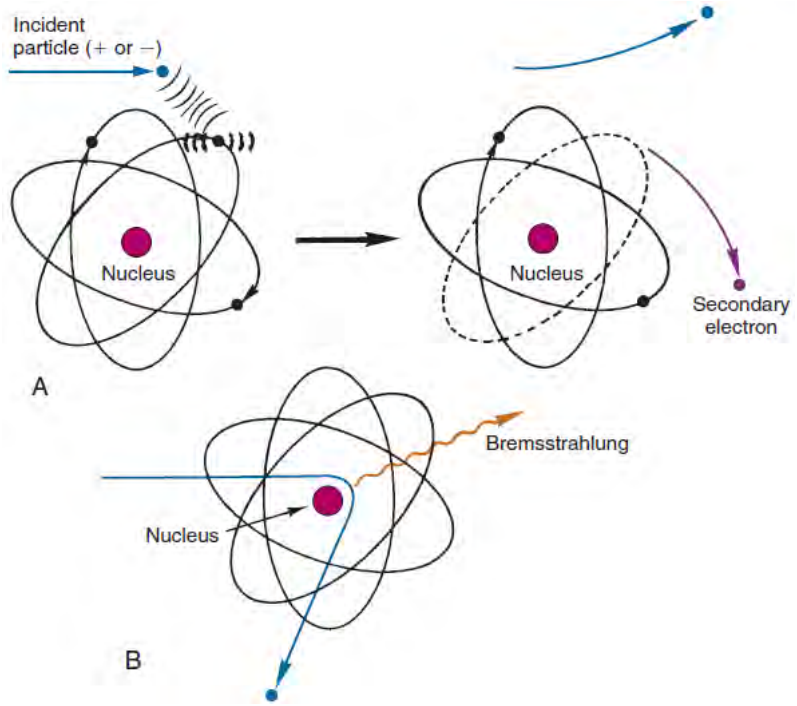


Figure 2.1: Schematic representation for charged particle interactions.

Source: Physics in Nuclear Medicine by Cherry et al, 2012, p.64 *E-Book*: Elsevier Health Sciences.

A represents Photon interaction with an outer electron resulting into ionization and ***B***, Interaction with a nucleus, resulting in bremsstrahlung production (Cherry et al, 2012).

2.2.2 **Interactions of Photons with Matter**

The energy of a photon is the major determinant of the mechanism by which it interacts with matter. The three main modes by which photons interact with matter to deposit their energy are discussed and illustrated in Figure 2.2 below. The boundaries show the values of Z and photon energy for which the effects are just equal.

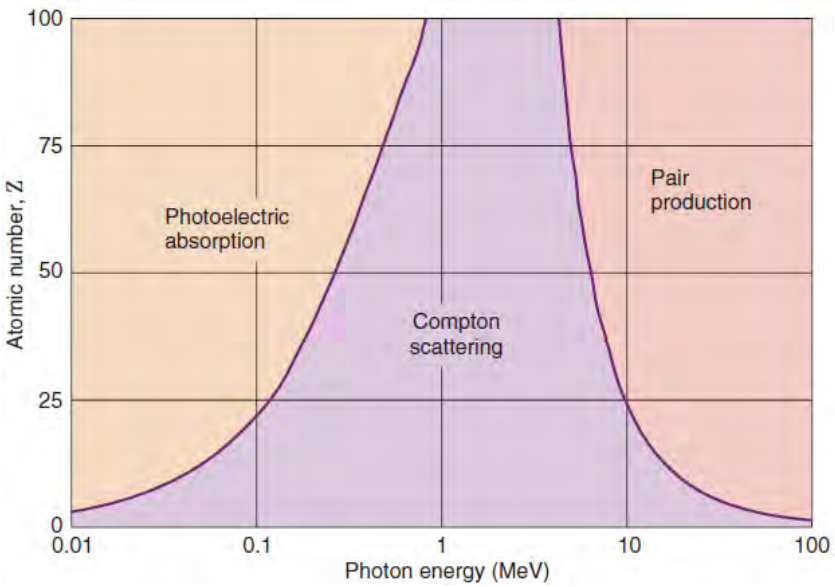


Figure 2.2: The three major photon interactions with matter for different energies.

Source: Physics in Nuclear Medicine by Cherry et al, 2012, p.81 *E-Book*: Elsevier Health Sciences.

Photoelectric Effect: In photoelectric effect an incoming photon interacts with and an electron which is bound to the atom. During this process, the photon is absorbed by the atom and an electron is ejected. The kinetic energy with which the photo-electron is ejected is equal to the difference between the energy of the incoming photon energy and the binding energy of the electron. In nuclear medicine, the photon energies of interest are between 30 and 300kev. This is due to the fact that, at these energies the electrons are more penetrating and thus able to participate in the photoelectric process. The photoelectric effect is therefore pre-dominant at low energies (interactions vary inversely as the third power of the energy). However, as photon energies become greater than the electron binding energies, the probability of the photoelectric process diminishes. At a certain energy, the number of photoelectric interactions per unit mass varies as the fourth power of the atomic number and is

inversely proportional to the atomic weight of the medium (Z^4/E^3A) (Powsner et al, 2013 and Cherry et al, 2012).

Compton Effect: The Compton Effect is the interaction of a photon with a free electron. If the energy of the incoming photon is much greater than the binding energy of the electron, the electron is said to be a free (unbound). The kinetic energy of the electron that is scattered is dependent upon the angle through which it is scattered. In order to impart all its energy to the medium, the scattered photon must continue to interact with the medium.

Compton Effect is pre-dominant for high photon energies (ranging from 100 keV to 10 MeV) for atomic numbers for detector materials. At 100 keV, the maximum kinetic energy of the scattered electron is about 30 % of the incoming photon; at 1 MeV, it is about 80 %; and at 10 MeV, about 98%. The number of Compton interactions per unit mass is approximately proportional with the energy the incoming photon and atomic number but inversely proportional to the atomic weight of the medium (ZE/A) (Cherry et al, 2012).

Pair Production: In the presence of the nuclear field, the incoming photon disappears and an electron-positron pair is produced. This process is called pair production. In order to produce an electron-positron pair, the incoming photon energy must be at least greater than 1.022 MeV (twice the mass of an electron). Pair production is pre-dominant at very high energies, that is, above about 10 MeV. The number of pair production interactions per unit mass is proportional to the square of the atomic number and inversely proportional to the atomic weight of the medium (Z^2E/A) (Powsner et al, 2013 and Cherry et al, 2012).

2.2.3 Gas filled detectors

As already seen above, the creation of ions is one of the results from the interaction of radiation with matter. This outcome is utilized by gas-filled detectors. In gas-filled detectors, the atoms of a gas are ionized by the radiation. Thus, the detector is the gas and can be used to measure radiation fields if the relationship between the radiation field and the charge produced is known. The radiation enters the detector and interacts with the gas or with the walls of the chamber. It must be pointed out that photons cannot produce ionization directly, but must first interact with the chamber material (gas and wall) to produce electrons (Maher et al, 2006).

That is, through a series of interactions, the photon transfers its energy to one or more electrons. The electron is slowed down through collisions with the chamber gas (argon). The collisions knock electrons off the molecules producing positive ions (this is the ionization process). An electric field is set up by the collection voltage across the chamber as positive ions drift towards the cathode and the electron drifts towards the anode, thus producing a current. The electronic circuitry then measures either the current or the total charge produced during the period of interest (Bailey et al, 2014 and Maher et al, 2006).

A gas-filled detector is commonly cylindrically shaped, with a well-insulated outer wall from a central electrode. Depending on the design of the detector and the voltage V_{dc} applied across the electrodes, its operation can fall in any of three regions (i.e. the ionization region B, proportional region C or Geiger–Müller (GM) region D) shown in Figure 2.3 below (Maher et al, 2006).

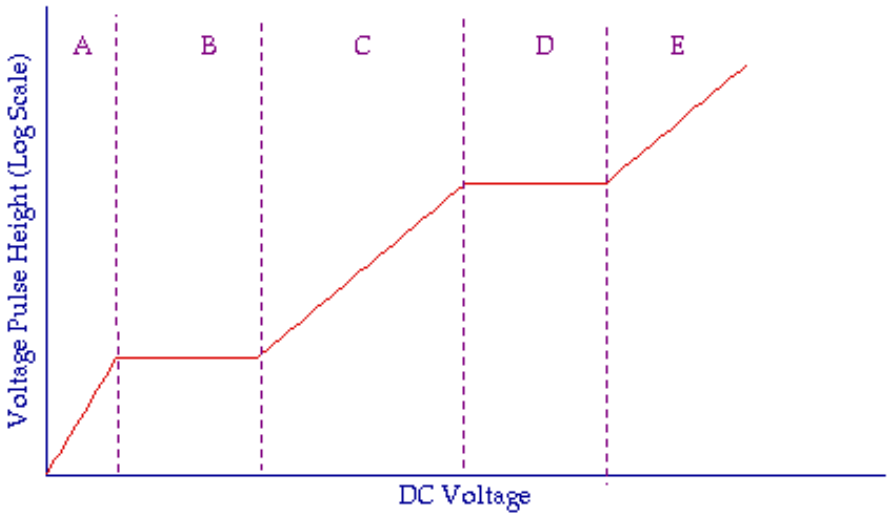


Figure 2.3: Graph showing the variation of the pulse height with voltage V_{dc} .

Source: Basic Physics of Nuclear Medicine by Maher et al, 2006, p.58. Libronomia Company: Wikibooks.

As be seen in Figure 2.3, the graph is divided into five main regions;

Region A: Here V_{dc} is very low and recombination of the electrons and positive ions takes place. Consequently, the pulse height is small due to the insufficient collection of ion pairs. As the applied voltage increases, recombination diminishes (Maher et al, 2006).

Region B: V_{dc} is appreciably high in this region so recombination is almost negligible. This region is called the ionization region and this is the operation region for a type of gas filled detector called ionization chamber**.** This is the region in which dose calibrators operate.

Region C: V_{dc} is sufficiently great to cause the electrons approaching the central wire to gain sufficient energy for collisions with the gas atom electrons to produce more ion pairs. Consequently, the number of electrons is increased so that the charge through the resistor may be very high (i.e. in the orders of thousand times) compared

to the charge produced primarily by the radiation interaction. A detector known as proportional counter operates in this region (Maher et al, 2006 and Podgorsak, 2005).

Region D: V_{dc} is so huge that even a weakly-ionizing particle creates a large voltage pulse. The primary ionization brought about by the radiation causes a complete gas breakdown as an avalanche of electrons drift towards and spreads along the central wire. This region is referred to as the Geiger-Müller Region and the detector that utilizes this it is called Geiger counter.

Region E: This region cannot be used for the detection of radiation events since any further rise in V_{dc} is sufficient enough to completely cause gas breakdown (Maher et al, 2006).

2.2.4 The modern radionuclide calibrator

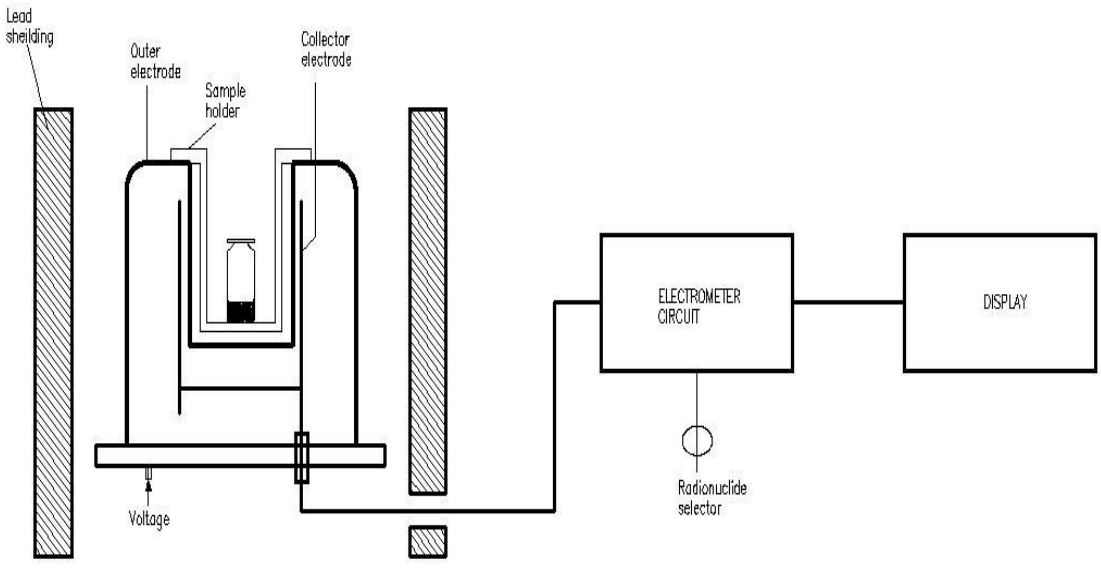


Figure 2.4: Schematic representation of a dose calibrator

The calibrated re-entrant ionization chamber is commonly referred to as a dose calibrator. The instrument is able of provide accurate radioactivity measurements within clinically acceptable levels when properly calibrated, operated, and serviced. The chamber is typically made of aluminum enclosed with argon under pressure (1-2 MPa or 10-20 atm). It has a perspex well lining material easily removable for cleaning to prevent the chamber from accidental contamination. A vial holder (dipper) into which a syringe or vial is placed is provided to maintain the source geometry and ensure optimal positioning within the chamber. The chamber is normally pre-shielded with 6mm of lead by the manufacturer in order to lower the influence of background radiation IAEA-TECDOC (1991).

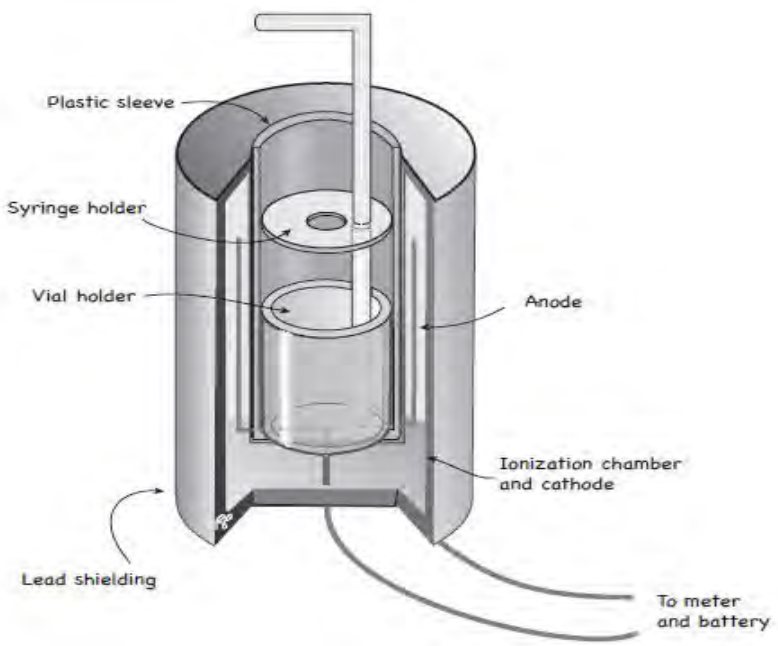


Figure 2.5: Radionuclide calibrator

Source: Essentials of Nuclear Medicine Physics and Instrumentation by Powsner et al, 2013, p.48. John Wiley & Sons.

Table 2.1 shows some specifications for two common radionuclide dose calibrators.

Table 2.1: Specifications for two common radionuclide calibrators

Specification	**Capintec CRC-25R**	**Atomiclab 200**
Ionization chamber dimensions	26cm deep×6cm diameter	26.7cmdeep×7cm diameter
Measurement range	Auto ranging from 0.001MBq to 250GBq	Auto ranging from 0.001MBq to 399.9GBq
Nuclide selection	8 pre-set, 5 user-defined (80radionuclide calibrations in memory)	10 pre-set, 3 user-defined (94radionuclide calibrations in manual)
Display units	Bq or Ci	Bq or Ci
Electrometer accuracy	<±2%	<±1%
Response time	Within 2s	1s for activities >75MBq
Repeatability	±1%	±0.3%

Source: Nuclear Medicine Physics: a Handbook for Teachers and Students by Bailey et al 2014, p.252. Vienna: International Atomic Energy Agency (IAEA).

2.2.1 **Absorbed dose via measurement of current or activity**

People or biological systems exposed to radiation are at potential risk of radiation dose being delivered. The quantity of energy deposited per unit mass is the absorbed dose. It is therefore important to distinguish between the activity of a radioactive source and the radiation dose which may result from the source. The radiation dose depends on the location of the source with regard to those exposed. Furthermore, the radiation dose depends upon the type of radiation, such as whether it is α, β or γ-rays and the energy of the radiation. The energy is transferred in small quantities for each interaction between the radiation and a molecule and there are usually many such interactions. Radiation results in the formation of positive and negative ions in a gas as well as in all other materials (Bailey et al, 2014).

When a syringe or vial enclosing the radioactive sample is placed into the source holder and gently lowered into the chamber, the inactive gas is ionized; ion pairs drift towards opposite polarity thus setting up an electrical current. This current between the electrodes is proportional to the activity of the assayed radioisotope. The magnitude of this current is usually small (on the microampere level) even if higher activity is used. It is for this reason that an electrometer is coupled to the dose calibrator in order to quantify this minimal electric current and convert the display into activity in MBq or mCi (Bailey et al, 2014 and Powsner, 2013).

2.3 CALIBRATION OF DOSE CALIBRATORS

Calibration involves the determination of a numerical relationship, with its associated uncertainty, between an observed measurement and its expected value using a standard system, based on reference sources, traceable to national primary standards of radioactivity. Traceability is the characteristic of a result or value of a standard by which it can be linked to some references, normally national or international standards, through a continuous chain of assessments, all having defined uncertainties (Gagnon et al, 2010 and Gadd et al, 2006).

Calibration of dose calibrators may also involve determining dial settings for each radioisotope to be assayed. Manufacturer calibration settings are given as dial settings (calibration factors) for individual radionuclides. However, these settings may vary slightly because the chamber response depends on the type of radionuclide, its geometry (source vessel type and volume) and height in the chamber. Therefore, in order to ensure accurate measurement for each radionuclide, the assay must be made using the appropriate calibration setting and correct geometry for which the system was calibrated (AAPM Report 181, 2012 and Gadd et al, 2006).

Sharma et al (2015) reported a cumulative error of about 20.0% with respect to the accuracy in the measurement of radioactivity for the beta-gamma emitters. There is consequently the need to redefine the manufacturers' quoted values of the calibration settings of the dose calibrators used in a given hospital-based clinical setting.

Although most dose calibrator are purchased pre-calibrated by the producer for frequently used radioisotopes, the dial values need periodical review as they are originally determined through measurements of primary or traceable standard sources for a master system before they are transferred to a production system as calibration settings. The settings can also be calculated using energy-response curves obtained using available decay schemes. It is recommended for medical facilities, radiopharmaceutical companies or commercial nuclear pharmacies to occasionally review and verify if these calibration settings are traceable to NIST standards (AAPM Report 181, 2012).

Tyler and Woods (2003) report significant differences between the dial values for syringes and glass vials due to different energy photon emissions from the decay of the radionuclides; the lower the energy, the greater the difference. Large differences were observed for ^{125}I and only small differences for ^{131}I. However, for radionuclides such as ^{99m}Tc and ^{67}Ga, variations of up to 30% have been observed indicating the importance of specifically derived calibration factors as well as emphasizing the complexity of the problem with regard to geometry influence.

2.3.1 **Energy-response Curves (Photons)**

Calibration settings for the chamber can be determined for individual radionuclides. The energy efficiency ε_N, of the ionization chamber for a radioactive source is given

by the reciprocal of the calibration setting and can be written as the summation of two components:

$$\varepsilon_N = \sum_i P_i(E_i)\varepsilon_i(E_i) \qquad (2.3.1)$$

Where

$P_i(E_i)$ is the emission probability for each disintegration of photons with energy E_i and $\varepsilon_i(E_i)$ is the efficiency of the chamber. A number of calibration coefficients are obtained using well known reference sources within required energy window. The chamber's response as a result of particular photons from the radioisotope is then determined, standardized to a reference source, and plotted to obtain the energy-response profile. Figure 2.6 below shows a characteristic curve using ^{60}Co as standard source for an aluminum alloy wall ionization chamber for a commercial radionuclide dose calibrator (Bailey et al, 2014 and AAPM Report 181, 2012).

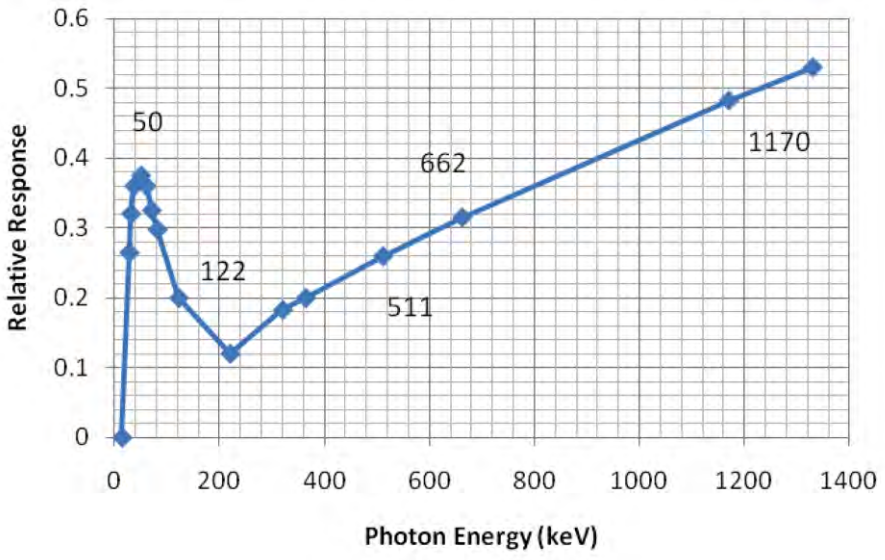


Figure 2.6: Energy-response curve using ^{60}Co as standard source.

Source: AAPM Report TG 181, 2012, p.10.

For aluminum-walled chambers, photons with energies around 13 keV are blocked from reaching the sensitive volume of the chamber. The actual threshold varies depending upon the source container wall material, its volume and thickness. The thickness differs from system to system due to manufacturing discrepancies. As seen in Figure 2.6, from a low-energy cut-off, ionization current rises sharply and then falls suddenly, producing a peak at roughly 50 keV. The peak is as a result of the opposing effects that a rise from photon transmission through the source, container and chamber wall (since photoelectric effect falls sharply), together with the subsequent reduction in photon interaction with the chamber volume. Compton scatter dominates at almost 50 keV. Above 200 keV Compton scatter is predominant and the response rises with increase in photon energy. Thus, efficiency is minimal at low energies, has a peak around 50 keV, drops to a minimum at 200 keV, before increasing proportionally to energy (Bailey et al, 2014 and AAPM Report 181, 2012).

2.3.2 Dial value or Calibration number (N_A)

The dial value or calibration number (N_A) is the factor dialed into the calibrator to give the desired gain. A calibration number helps to convert the measured current to a nominal activity. This means that a dose calibrator requires a different dial value for each individual radioisotope to be measured (Prekeges, 2012).

The size of a calibration factor is also determined by the chamber (thickness of inner wall, pressure of the gas, design, and applied voltage), geometry of source (vessel type, thickness, its volume) and location of the sample in the chamber (Prekeges, 2012 and Capintec 2007).

2.3.3 Determining dial values for Capintec dose calibrator (Capintec 2007, 2015).

It is very convenient to express the response R_N of the detector to a radioisotope, N, relative to that of a standard reference material (SRM), e.g. Co-60.

$$R_N \equiv \frac{\left(\frac{\text{Detector Output due to Sample N}}{\text{Activity of Sample N}}\right)}{\left(\frac{\text{Detector Output due to SRM Co} - 60}{\text{Certified Activity of SRM Co} - 60}\right)} \qquad (2.3.2)$$

The sensitivity S_i of the detector for a photon of energy E_i is defined as:

$$S_i \equiv \frac{\text{Detector Output due to } 3.7 \times 10^{10} \text{ Photons of } S_i}{\text{Dtector Output due to one Curie of Co} - 60} \qquad (2.3.3)$$

The detector response R_i and the sensitivity have the following relation:

$$R_i \equiv \sum_i I_i S_i \qquad (2.3.4)$$

Where I_i is the intensity of the photon whose energy is E_i.

The relationship between the response of the detector and the gain setting G_A (relative to that for ^{60}Co, in order for the instrument to give a direct reading of the activity) is given by:

$$G_A \equiv \frac{1}{R_N} \qquad (2.3.5)$$

Capintec calibrators are calibrated with certified Cobalt-60 and Cobalt-57 standard radionuclide sources. The calibration setting number N_A of Capintec Calibrators for a radioisotope A, is given by

$$N_A = \left(R_N - \left(1 - \frac{R_{Co-60} - R_{Co-57}}{N_{Co-60} - N_{Co-57}}\right) * N_{Co-60}\right) * \left(\frac{N_{Co-60} - N_{Co-57}}{R_{Co-60} - R_{Co-57}}\right) \qquad (2.3.6)$$

Where:

$N_{Co\text{-}60}$ and $N_{Co\text{-}57,}$ and $R_{Co\text{-}60}$ and $R_{Co\text{-}57}$ are the calibration numbers and responses for ^{60}Co and ^{60}Co standard radionuclide sources respectively. For Capintec these are assigned the following numbers:

$N_{Co\text{-}60} = 990$, $N_{Co\text{-}57} = 112$

$R_{Co60} = 1.000$, $R_{Co-57} = 0.189 \pm 2\%$

Substituting the values for $N_{Co\text{-}60}$ and $N_{Co\text{-}57,}$ and $R_{Co\text{-}60}$ and $R_{Co\text{-}57}$ into equation (2.3.6) equation (2.3.7) below is obtained:

$$N_A \equiv 1076(R_N - 0.080) \qquad (2.3.7)$$

However, as seen in equation (2.3.5) the gain G_A is inversely proportional to the response R_N, we can therefore rewrite (2.3.7) as:

$$G_A \equiv \frac{1}{\frac{N_A}{1076} + 0.08} \qquad (2.3.8)$$

The accuracy of the sensitivity curve and calibration number determined are tested by calculating calibration numbers for all radioisotope standards used for the studies of the sensitivity. The agreement between the calculated and observed responses should be within ±3% tolerance (Capintec 2007, 2015).

2.4 DOSE CALIBRATOR QUALITY CONTROL TESTS

2.4.1 Quality Assurance and Quality Control

For dose calibrators quality Assurance (QA) is a systematic tool for checking and evaluating the attainment of high standards of efficiency and reliability in the practice. It encompasses management plans to guarantee the dependability of the production system. QA helps in minimizing the uncertainties and errors in equipment performance. Quality Control (QC) refers to the specific measures put into place to ensure that each particular aspect of the procedure is reliable (IEC TR 61948-4, 2006 and IAEA-TECDOC, 1991).

Specifically, QC is part of the QA programme and is essential for the submission of requirements for procedures; the preparation and administration of radiopharmaceuticals. QC is essential for radiation protection of patients, staff and the general public. It also serves as an important component in the preparation of patients; the setting-up, use and repairs of electronic devices; the method of the actual procedures; the investigation and interpretation of images; the reporting of results and, finally, for record keeping . A radionuclide dose calibrator must therefore be covered by a comprehensive QA programme. It is important to carry out the test procedures correctly since the safety of the patient is highly reliant on the accuracy of measurements from the radionuclide dose calibrator. Often, procedural errors in performing QC on calibrators seem to be unavoidable even by experienced users. It is therefore important to adhere to guidelines given in the user manual. The QC tests performed on dose calibrators are shown in Table 2.2 (IAEA TRS 454, 2006 and IAEA-TECDOC, 1991).

Table 2.2: Dose calibrator quality control tests

QC test	Frequency	Source	Half-life	Energy (keV)
Constancy Check	Daily	^{137}Cs	30 years	662
Linearity response test	Installation, quarterly, After repairs and when displaced to new location.	^{99m}Tc	6hours	140
Accuracy test	Installation, annually and after repairs.	^{60}Co	5.3years	1170, 1330
		^{137}Cs	30 years	662
		^{133}Ba	10.51 years	356
		^{57}Co	271.7 days	122
Geometry test	Installation and after repairs.	^{99m}Tc	6 hours	140

2.4.2 **Constancy check**

Constancy means reproducing a measurement result whenever the same source is assayed over a period of time, taking into account its decay. Constancy test measures the dose calibrator's ability to give reproducible readings daily on all available radioisotope windows likely to be encountered. This test should be performed daily using a long-lived source, usually ^{137}Cs. It is strongly recommended that the same source be readily available for use throughout the life of the calibrator. Variations in displayed activities must fall within ± 5% of the most recent reading at that setting with background and decay considered (de Farias Fragoso, 2013 and IAEA-TECDOC, 1999).

2.4.3 **Linearity of response test**

Linearity testing measures the ability of the calibrator to give the correct reading over the entire range of activities of its usage. The test is performed at installation and quarterly and using a syringe or vial of ^{99m}Tc with activity as high as the maximum normally prepared in radiopharmaceutical kit, in a unit dosage syringe administered to a patient, or in therapy, whichever is largest. In a Mo-99/Tc-99m generator this activity may be the total eluate in a radiopharmaceutical kit. It is recommended to carry out the test at installation, quarterly, after repairs and if there is displacement to new location (Ahmed, 2015 and Mo et al, 2006).

Linearity test can be performed using a number of methods (i.e. decay, shielding and proportional methods). The decay method involves assaying a high activity of a short-lived radionuclide, normally ^{99m}Tc source at an initial time T_0 and at pre-determined intervals of time until activity falls below 30 μCi. The expected and measured activities are compared to ascertain the instrument's linearity over the entire range of activities. This test also reveals the region and extent of non-linearity arising from saturation effects (ion-recombination); non-linearity near to zero activity (may indicate a wrong preset zero adjustment) and discontinuities at change of range (systematic error in one of the ranges). The activity measured should be within ± 5% of its predicted value if the instrument is working properly (IAEA TRS 454, 2006 and IAEA-TECDOC, 1991).

For the first calibration or reinstallation, the decay method is suitable for determining calibration factors to be subsequently used for the shielding method. There are several manufacturers of sets of lead lining that may be used for performing the linearity test using the shield method. The kit might have tubes of different colors representing different thicknesses of lead-lining. It may also have numbered and

lettered cylinders of different thicknesses and different linings that are used in combination, each having different amounts of shielding to mimic intervals of ^{99m}Tc decay. These sets are calibrated when first acquired by ordering a 100 mCi ^{99m}Tc source and performing the linearity by the decay method as well as by the shield method. At the beginning of the decay calibration, measurements are also made with the tubes. The decayed measurements are used to verify that the calibrator had a linear response at the time of the cylinder calibrations for period of about 72 hours (Ahmed, 2015 and Capintec 2004).

If the calibrator passes that test, then the tube attenuation measurements can be used as a calibration for all future linearity tests. A 100 mCi source is acquired and measured inside each of the tubes. The measured activity of each tube relative to no tube should be the same as the calibrated ratios. This then confirms maintenance of a linear response and is completed in just a few minutes.

The proportional method of determining the linearity response can be confirmed by measuring the activity of a sample and then checking the activity of carefully weighed portions of the sample. The minimum activity of the initial sample should be as large as the highest activity normally measured. The ratio of the measured activities should be the same as the ratio of the measured weights or volumes (i.e. within ±0.5% uncertainty). The weights or volumes must be measured to a degree of accuracy much greater than the expected linearity (Capintec, 2007 and IAEA-TECDOC, 1991).

2.4.4 **Accuracy test**

Accuracy is a measure of how close an observation is to the true value. It means that for given standard reference source, the indicated activity corresponds to the reading determined by NIST or the provider who has compared that source to one calibrated by the NIST. For a radionuclide calibrator, accuracy test is intended to indicate whether the calibrator gives correct readings over the entire energy scale (low, medium, and high) likely to be encountered from energy standards. Long-lived radionuclide sources, such as ^{137}Cs (Energy = 662 keV) and ^{57}Co (Energy = 122 keV), are repeatedly assayed in the calibrator and the mean of the measurements are compared with the decay-corrected values within stated tolerances issued by NIST for that particular reference source. If the readings differ significantly (>10%) from the standards then the calibrator should not be used. The test should be done at installation, annually, and after repairs or when the instrument is moved to a new location within the medical facility (Powsner et al, 2013 and IAEA TRS 454, 2006).

Zeinali et al (2008) reported eight Nuclear Medicine centres in unacceptable situations with regards to dose calibrator assay accuracy. The study found two centres within 70% uncertainty, four over 30%, one had 28%, and the other one had 16% in terms of deviations in the measurement of the calibrated radionuclide standards.

2.4.5 **Geometry test**

The geometry test is intended to show that accurate measurements can be obtained independent of the sample geometry or size. This test is done using a syringe that is normally used for injection. If volumes of syringes and vials differ from the recommended, they must be tested throughout the range of volumes commonly used. The test is performed at installation and after repairs. Volume correction factor

(VCF) can be applied if the geometry test is within ±5% or else the calibrator must not be used (Powsner et al, 2013, Assan et al, 2012 and IAEA TRS 454, 2006).

2.4.6 **Standards relating to dose calibrators**

The International Electrotechnical Commission (IEC, 1992; 1994) and a Technical Report (IEC/TR 61948-4, 2006) are two standards that apply to dose calibrators. IEC standards are often adopted by national standards organizations. Most manufacturers use IEC (1992) guidelines to ensure proper equipment functioning in a standardized way, while IEC (1994) is intended for operators of dose calibrators. On the other hand, the American National Standards Institute publication ANSI N42.13 (2004) is also often referenced by US manufacturers. ANSI states the least requirements of accuracy and repeatability for dose calibrators. The recommended assay accuracy of a reference source (activity above 3.7MBq) in a calibrator must be within ±10% of the stated activity with decay correction. The reproducibility must be within ±5% of the mean reading for that source from a series of ten consecutive measurements with activity larger than 100μCi (3.7MBq) in the same geometry. See Table below for some limits for of acceptability for some standards for dose calibrators. Table 2.3 shows some of the limits of acceptability for dose calibrators (Bailey et al, 2014, IEC TR 61948-4, 2006 and ANSI N42.13, 2004).

Table 2.3: Limits of acceptability for different standards for dose calibrators

	Background	Reproducibility (stability)	Relative response	Accuracy	Linearity	Geometry
ANSI		±5%	±5%	±10%	±5%	----
IAEA	±20%	±5%	±5%	±5%	±10%	±5% ±2%
NCRP		±5%	±5%	±5%	±5%	
AAPM		±5%	±5%	±5%	±5%	----

2.5 SOME SOURCES OF ASSAY ERRORS

2.5.1 User errors

Most dose calibrator systems are user friendly if properly set up and operated as directed in the manufacturer's user guide. It is important for users to understand the calibrator's functionalities and characteristics. It is the duty of the licensee to ensure proper training is given to individuals who use the calibrator. QC tests are to be done as required by the manufacturer and suitable action taken if errors are outside recommended limits. Users of dose calibrator must understand that calibration numbers are unique for each radionuclide and are specific to the geometry of source. Therefore, dippers must be used as indicated by the manufacturer and should be correctly positioned in the chamber, without physical alteration or damage. Dippers from different companies should not be exchanged without considering the influence on the accuracy of the calibration coefficients (AAPM Report 181, 2012).

2.5.2 Calibration geometry

Ideally, manufacturers of dose calibrators calibrate their systems based on the type of radioisotope and the sample geometry used practically. However, this may not always be the case since calibrations must be derived for each container type and specific source geometry. Therefore, calibration settings derived by the manufacturer can be a source of assay error since they are prone to minor fluctuations in position and source configurations. This means that, any variation in these parameters may have a bearing on the accuracy of the measurement. It is up to the operator to verify whether the change is insignificant (<5%) or, if significant (>10%), new dial values need to be determined (AAPM Report 181, 2012 and Baker et al, 2005).

Baker et al (2005) have observed significant deviations in terms of assay accuracy for ^{99m}Tc isotope. The accuracy in a number of cases was better than 5%. Precisely, 2% of the assays fell within 2% of the expected activity, 96% were within 5%, and only one assay was more than 10%. In this case the manufacturer's assigned dial values were used. Nevertheless, the study did not reveal errors due to using geometry since measurements were done in the same geometry as calibrated.

2.5.3 Effects of an external shield

The external shielding of the radionuclide calibrator provided by millimeters of lead has several advantages. It helps in the reduction of the background effects on the activity measurements, reduces radiation exposure to the personnel handling the radioisotopes and prevents efficiency changes caused by scattering material in the vicinity. The manufacturer normally shields the chamber with 6 mm of lead to minimize external influence on the system background (Gadd et al, 2006).

However, the back scattering of photons and the emission of Pb K shell X-rays as a result of interactions within the lead shielding will modify the calibration factors. If extra shielding is needed, then the calibrator must be re-calibrated or correction factors should be determined to ensure correct readings are obtained. It is also worth noting that a shield positioned around or near a calibrator improves the sensitivity of the ionization chamber due to backscattering of photons by the shielding. For a Capintec calibrator the backscattering effects are more significant for photons of energies between 70 keV and 250 keV than photons in other energy regions (Capintec 2007).

2.5.4 **Effects of container material**

Radioactive standard materials in the containers now being provided by NIST give a fair estimate of the assay of a radionuclide in a plastic or glass syringe (wall thickness of 1.2 mm), even for radioisotopes with abundant low-energy photons. The operator should select, whenever possible, a standardized method, volume, and vessel for assaying radionuclides. The plastic syringe is suitable since it represents the delivery vehicle to the patient in most clinical conditions. Significant errors will occur in some instances, e.g., if the radioisotope is assayed in an appreciably different material and/or wall thickness than that of the standards. The vessels of most available standards from NIST are uniform. Plastic syringes also have a rather uniform wall thickness with low absorption (Capintec, 2007).

2.5.5 **Effects of impurities**

The presence of radioisotope impurities affects the reading of the radionuclide dose calibrator, particularly in measurements of short-lived radionuclides several half-lives after initial preparation (unless this effect is removed by photon filtration as with ^{99}Mo breakthrough in ^{99m}Tc). An ionization chamber itself does not have intrinsic energy- discrimination ability. The existence of radioisotope impurities will affect the reading of the calibrator unless the effect of impurities is eliminated by photon filtration as is done with ^{99}Mo breakthrough in ^{99m}Tc. However, the presence of low-level radionuclide impurity does not negate the effectiveness of a dose calibrator, if the operator is aware of its presence and has an independently determined calibration including photons due to the impurities (Capintec, 2007).

2.5.6 **Drift in the electronics of the calibrator**

The accuracy of the electrometer is another source of uncertainty over which the user may have little control. The electrometers' inherent accuracy depends on the ability of the supplier to adjust the gain of the electrometer so that its measurement of current is traceable to primary standards. The adjustment is normally achieved by measuring the response of the system to a long-lived standard reference source and adjusting the electrometer gain until it indicates the true activity within the manufacturing tolerance. The gain of the system, however, will change with time and environment. This results from normal ageing effects of electrical components, such as resistors and capacitors, as well as the temperature, humidity and radiation exposure dependence of these components. If a reference source is supplied with the chamber, this allows the user of the facility to produce a benchmark reading when it is first supplied and to then adjust the electrometer gain if it changes with time (Gadd et al, 2006).

The electrometer linearity is another source of uncertainty. The response is regarded as linear if the ratio of the measured response to the true response remains constant over the range of current inputs for which the calibrator is designed. Electrometers are expected to measure currents within a deviation from provided this is contained within reasonable limits; it may not be a significant problem (Gadd et al, 2006).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter presents the materials used to accomplish the study and the methods involved in arriving at the results. The materials include equipment and software used for the study. The study is an experimental study carried out at Korle-Bu Teaching Hospital in Accra-Ghana. The QC tests in this work were conducted in accordance with well-established and accepted international standards for dose calibrators (AAPM Report 181, 2012, IAEA TRS 454, 2006 and IAEA-TECDOC 602, 1991).

3.2 MATERIALS USED FOR THIS RESEARCH

Figure 3.1: Some materials used for the study

Others: Non-radioactive saline solution and 773 mCi (28.6 GBq) of ^{99m}Tc activity

3.2.1 **Materials and equipment**

Table 3.1 shows specifications for Capintec CRC®-15R and Comecer FHG LAF 40C1F dose calibrators were used in this study.

Table 3.1: Specifications for Capintec CRC-15R and Comecer dose calibrators

Specification	Capintec CRC-15R	Comecer FHG LAF 40C1F
Chamber dimensions	25.4 cm deep×6.1 cm diameter	28 cm deep×7 cm diameter
Weight	13.6 kg	4 kg
Resolution	0.001 MBq	0.15 MBq
Measurement range	Auto ranging from 0.001MBq to 250 GBq	Auto ranging from 0.15MBq to 185 GBq
Nuclide selection	9 pre-set, 4 user-defined radionuclide keys	28 pre-set, user-defined radionuclides keys
Unit of display	Bq or Ci	Bq or Ci
Electrometer accuracy	Better than ±2%	Better than ±2%
Response time	Within 4s-16s	1s -10s
Repeatability	±1%	±1.5%

3.2.2 **Comecer Dose Calibrator**

One of the most prominent manufacturers of dose calibrators for use in nuclear medicine units is Comecer. The fully digitized detector systems in Comecer models give quick and dependable read-out. This enables flexible integration of this detector into other systems or facilities, without the need of a converter or separate read-out. Comecer also has unit-measurement range of up to 2 Ci for ^{18}F used in PET systems.

Figure 3.2 below shows Comecer FHG LAF 40C1F calibrator in a radiochemistry fume hood system at Korle-Bu Teaching Hospital.

Figure 3.2: FHG LAF shielded Radiochemistry Cappa/fume hood with Comecer dose calibrator.

3.2.3 **Capintec Dose Calibrator**

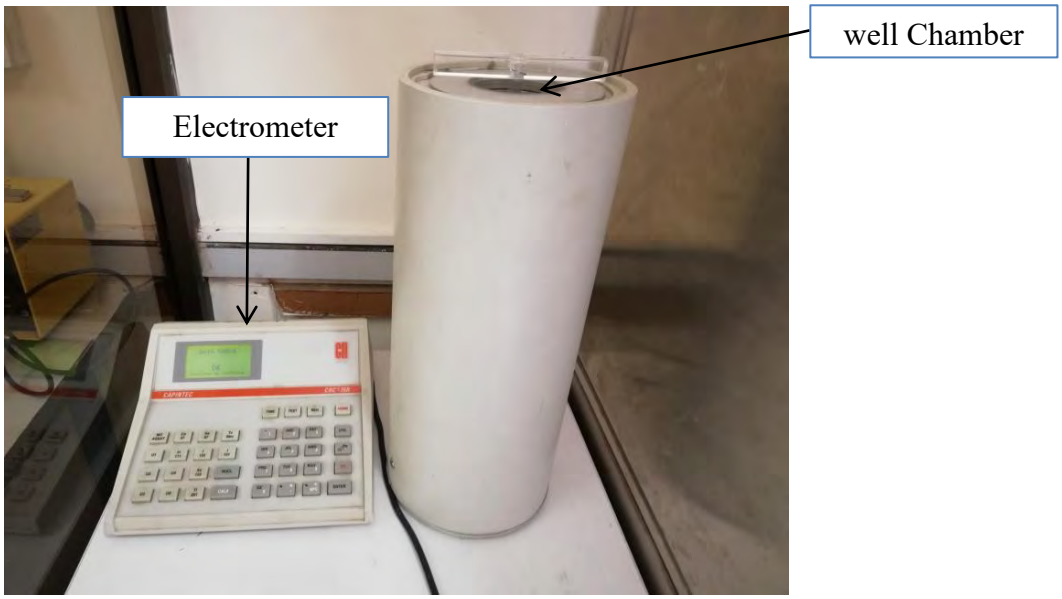


Figure 3.3: Capintec CRC-15R dose calibrator

Capintec CRC-15R dose calibrator RAMSEY, N.J 07446 made in U.S.A. P/N 7120-2204 manufactured in 1999 by Capintec was used in this study (see Figure 3.3). It is

one of the most known dose calibrators because of its speed, simplicity and accuracy. This system takes advantage of the latest technology of auto-ranging for varying sample activity, giving it added speed, accuracy, and easy to use features.

3.2.4 Standard radionuclide source

A long-lived ^{137}Cs standard radionuclide sealed source in vial form (Code no. CDR562) of activity 9.21 MBq (248.92 μCi) calibrated for 13th October, 2005 and manufactured by AEA Technology QSA GmbH was used for constancy, relative response and accuracy tests.

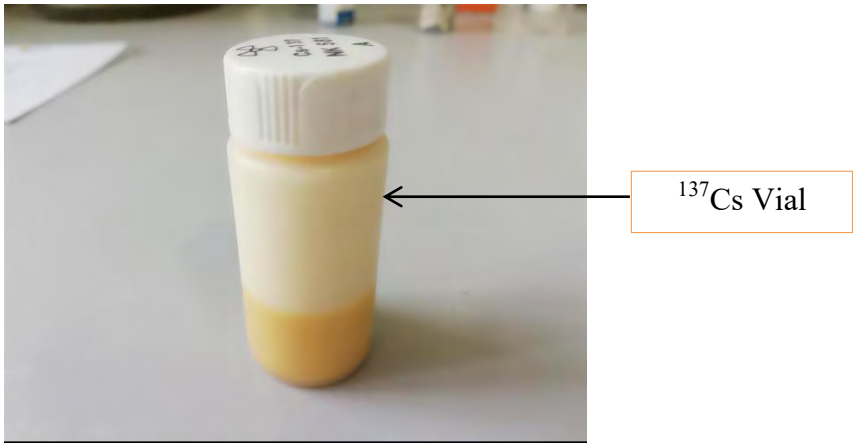


Figure 3.4: Vial containing ^{137}Cs standard radionuclide source

3.3 SOFTWARE

3.3.1 Microsoft Excel 2010

The data collected was analyzed using Microsoft office 2010-Excel Program under windows 10. Microsoft Excel is a general spreadsheet software program for sorting, compiling and highlighting huge quantities of data. With new features such as spark

lines and slicers, and improvements to Pivot Tables and other existing features, this version makes it easy to discover patterns or trends in the data.

Finally, the multi-threading feature in Microsoft Excel 2010 helps speed up data retrieval, sorting, and other performance enhancements. These and many other features made the software suitable for use in data analysis for this study.

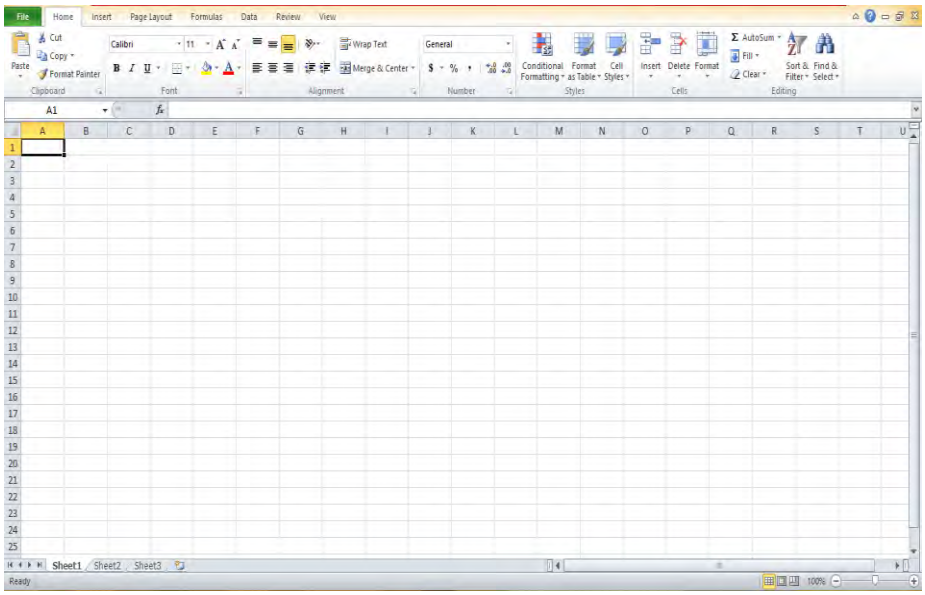


Figure 3.5: Interface for Microsoft Excel 2010

3.3.2 **Minitab 16 software**

Minitab is statistical software package used for all-purpose instructional application with easy interactive tools. Minitab was used due to its well suited capability to model systems making it a powerful primary tool for analyzing research data.

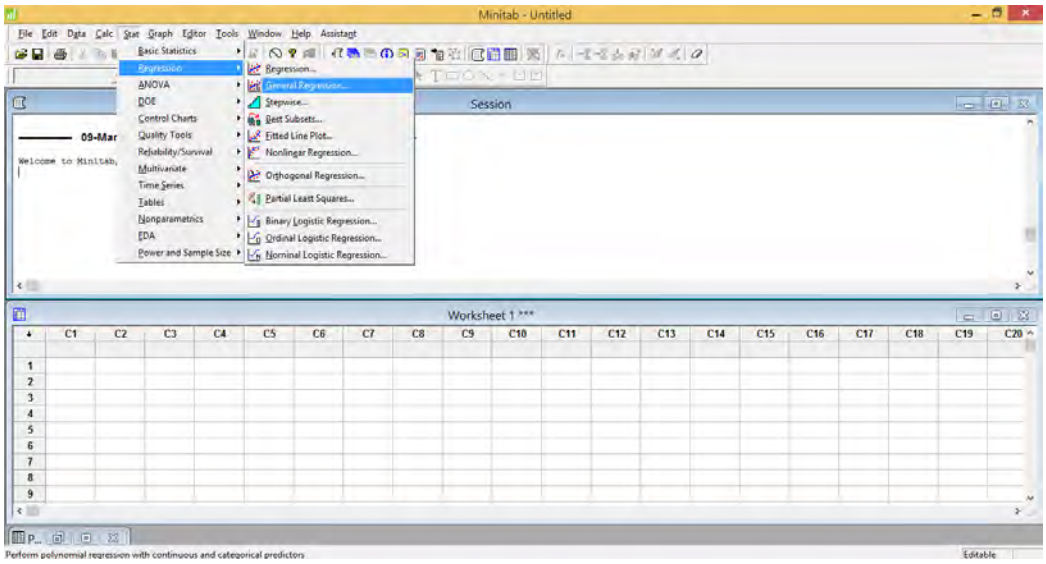


Figure 3.6: Interface for Minitab 16 software

3.4 Methods

3.4.1 Physical inspection

This involved inspecting both radionuclide calibrators' general condition.

The housing and particularly surroundings of the ionization chamber were examined for damage. Then compatibility of power supply requirements, controls, plug-in modules, push-buttons and switches were also checked. Other connections were also inspected for availability or physical damage. The condition of remote handling devices, source holders, well liners and ^{99}Mo breakthrough kits were inspected. All additional standard sealed sources were checked. Finally, operation and service manuals, and instrument log-book were located.

3.4.2 Performance checks

The daily performance checks on both radionuclide calibrators included auto zero, a background check, high voltage test and constancy checks.

Without the presence of any radionuclide source in the well chamber or its vicinity, the key for daily performance checks was selected. Auto zero check was initiated and the displayed millivolt reading was recorded. The background check was initiated by choosing ―next test" from the prompt options at the finish of auto zero check. The minimum background activity of the system was accepted and noted. Auto zero and background tests make it possible to identify any eventual residual contamination in the well of the detector.

Finally, high voltage test was initiated and the stable reading of the displayed system biasing voltage was noted. For battery alimented detectors, this test makes it possible to verify if the biasing volatge is within tolerance to avoid the recombination region.These tests were done on daily basis and the mean values were compared with manufacturer's specifications within their stated tolerance. Results were tabulated.

3.4.3 **Constancy check**

This test was done in addition to the daily auto zero, background and system tests. A long-lived ^{137}Cs standard radionuclide source in vial form (source number NK 581) of activity 9.21 MBq (248.92 µCi) calibrated for 13th October, 2005 and manufactured by AEA Technology QSA GmbH was used for this check. The appropriate operating conditions for data check were selected. The background at the ^{137}Cs setting was noted. With the aid of forceps, the check source was placed into the source holder and gently lowered into the well chamber of the calibrator. The reading was noted after 10s. 10s was chosen because it gives an optimum value of the response time for Capintec and Comecer dose calibrators (see Table 3.1). The net

result was obtained by subtracting the background from the measurement. The result was recorded and this procedure was repeated three times. The mean and its associated standard deviation were calculated.

Relative response test was also done with the ^{137}Cs check source assayed at the ^{137}Cs, ^{99m}Tc, ^{57}Co, ^{131}I, ^{67}Ga, ^{133}Xe and ^{201}Tl radionuclide settings taking into account the background for each radionuclide window. The net readings were then recorded. The test was done once every week and the results were tabulated.

3.4.4 **Accuracy test**

The appropriate operating conditions were selected for the ^{137}Cs standard radionuclide source. The background at this setting was noted. With the aid of forceps, the ^{137}Cs standard radionuclide source of activity 9.21 MBq (248.92 µCi) was placed into the source holder and gently lowered into the well chamber of the calibrator. The net reading was noted after 10s.The procedure was repeated three times and the mean of the measured activity was compared to the decay-corrected activity of the check source. Accuracy was calculated using the formula;

$$\%\text{Error} = \frac{\text{Mean measured Activity} - \text{Expected Activity}}{\text{Expected Activity}} \times 100 \qquad (3.4.1)$$

3.4.5 **Linearity test**

A 10ml vial containing 773 mCi (28.6 GBq) of ^{99m}Tc prepared from the eluate of a fresh generator whose molybdenum breakthrough test was 0.023 µCi/mCi was used for this test. The appropriate operating conditions for ^{99m}Tc radionuclide were selected on the calibrator and the background was noted at this setting. With the use

of forceps, a 10ml vial containing ^{99m}Tc source activity was placed into the source holder and gently lowered into the chamber well of the calibrator. The stable reading was recorded after 10s. The measured activity, time and date were noted. The activity was then assayed after 2, 6, 18, 30, 36, 40, 42, 48, 68, 74 and 94 hours respectively. For each assay; the background, measured activity, date and time were recorded. The expected activity of ^{99m}Tc was calculated for each time elapsed and the results were tabulated.

3.4.6 **Geometry test**

The constant activity method was employed in this study. This involved the addition of gravimetrically determined cumulative volume (10-100%) of non-radioactive saline solution to a sample volume of known ^{99m}Tc activity in a vial or syringe. The appropriate operating conditions for ^{99m}Tc radionuclide were selected on the calibrator and the background was noted at this setting. To ensure reproducibility in the source geometry, the same source holder was used throughout the test and the vial/syringe placed in the center of the source holder. For Comecer dose calibrator the correct geometry (vial or syringe) was also chosen from the console.

A 10 ml vial containing 1ml of ^{99m}Tc activity 56.67 mCi was placed into the sample holder with the aid of forceps. The vial was gently lowered into the chamber well and the reading was recorded after 10s. The measured activity and time was noted for both calibrators. The 10ml vial was removed from the chamber well and 0.5 ml of non-radioactive saline solution was carefully added to it using a 2 cc syringe. To help dilute the source volume easily and to avoid bubble formation, a bent needle was

inserted into the septum of the vial. The vial was then assayed in the calibrator. The measured activity, time and volume of saline were noted for both calibrators.

This procedure was repeated each time increasing the volume of saline solution in steps of 0.5ml until the vial reached a total volume of 6 ml. This procedure was now repeated with 1.66 mCi and 1.81 mCi of ^{99m}Tc activity in 2cc and 5 cc syringes respectively. The mean of the measured activity was compared with the decay-corrected activity for each volume and time elapsed. Volume correction factors (VCF) were calculated using the equation:

$$\mathrm{VCF} = \frac{\text{Activity of reference volume}}{\text{Activity of sample volume } V_i} \qquad (3.4.2)$$

The 3mL sample volume was chosen as reference volume for the calculation of VCFs for the 10mL vial while the 1mL was chosen for the 2 cc and 5 cc syringes respectively.

3.4.7 **Contamination test**

This test was performed twice every week. This involved measuring the background at the ^{137}Cs setting to check the dipper and/or well liner for any residual contamination at the end of a work day.

Without the presence of any radionuclide source in the well chamber or its vicinity, the ^{137}Cs window selected. The background at this setting was noted with the dipper (source holder) and liner in the well. The dipper was removed from the well and the background activity was noted. Finally, the well liner was also removed and the background noted. The liner was returned to the well to avoid contaminating the

chamber well. The amount of contamination was calculated from the differences between the background activities with and without liner and dipper.

3.4.8 Other Statistical methods

Statistical analysis was performed to clean out outliers from random data using the maximum minimum criterion of inclusion. In certain instances the data was normalized to a value of interest (e.g. mean, true value etc.) within the specified error margin of standard protocols for the test. Regression analysis was performed to find the extent to which the dependent is influenced by independent variable. T-test was also used for score variations and p-value was calculated to show if there is any significant impact of a test. Finally results were validated and the developed model was also assessed practically.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter, the results obtained from chapter three are discussed. The results are categorized into quality control, performance evaluation, cross-calibration and validation of results.

4.1 Quality Control

Table 4.1: Physical inspection

Nature of inspection	Comecer system	Capintec system
Housing/physical damage	No damages	No damages
Power supply	Compatible	Compatible
Remote handling devices,	Two available and in good condition	Two available and in good condition
Source holders	One available, not broken	Three available, one is broken
Well liners	Available	Available
^{99}Mo breakthrough kit	Available and in good condition	Available and in good condition
Standard Sealed Sources	Only ^{137}Cs standards available	Only ^{137}Cs standards available
User/service manuals	available	available
Instrument log-book	Reccords not found	Reccords not found

As seen in Table 4.1, both calibrators were found in acceptable conditions with regards to physical inspection checks according to recommendations by IAEA-TECDOC-602 (1991). However, the instrument log book could not be found for both systems.

4.2 Daily quality control

Table 4.2: Daily tests on Capintec

Test	Result	Criterion	Remark
Auto Zero (mV)	0.049 ± 7.14%	± 0.05 mV	*passed*
Background (µCi)	52.90 ± 7.72 µCi	27-500 µCi	*passed*
High voltage test(V)	0-0.15	155 ±15.5 V	*failed*
	162.6-162.9	155 ±15.5 V	*passed*
Data Check Cs-137 (µCi)	191.9± 2.6%	±5% or ±10%	*passed*

With the evaluation criterion stipulated by Capintec (2007 and 2015) operation and service manuals, and recommendations given in IAEA TRS 454 (2006) and IAEA-TECDOC-602 (1991), daily performance tests for Capintec were within acceptable limits. However, it was observed that the high voltage test failed for five cases. This could have been due to an inherent inaccuracy in the electrometer leading to failure in registering bias voltage. Despite the electrometer failure, all data checks with ^{137}Cs standard radionuclide source were found to be within the acceptable tolerance of ±5% indicating the presence of proper biasing voltage. This was an indication of drifts in the electronics of Capintec system.

Table 4.3: Daily tests on Comecer

Test	Result	Criterion	Remark
System Background	20.20 ± 8.61%	±20%	*passed*
High voltage test(V)	500	500	*passed*
Data Check Cs-137 (µCi)	191.87 ±1.62%	±5% or ±10%	*passed*

With the evaluation criterion stipulated by Comecer (2010) operation and service manuals and the recommendations given IAEA TRS 454 (2006) and IAEA-TECDOC-602 (1991), it was observed that all daily performance tests on Comecer dose calibartor were within acceptable limits.

4.3 Constancy check

Table 4.4: Constancy check on Comecer and Capintec systems

^{137}Cs Activity (µCi)	Comecer	Capintec
Measured Mean activity	185.1±1.2%	193.7±0.74%
SD	2.2	1.4

With the tolerance levels of ±5% recommended by IAEA TRS 454 (2006), both Comecer and Capintec dose calibrators were found to be within acceptable deviations of 1.2% and 0.74% for constancy test using 187.8 µCi of ^{137}Cs standard radionuclide source. This indicated that Capintec had better reproducibility than Comecer in terms of assaying ^{137}Cs standards. The mean activities of ^{137}Cs source with the associated standard deviations for Comecer and Capintec over a period of 18 weeks were found to be 185.1±2.4 µCi and 193.7±1.4 µCi respectively.

As also seen in Figure 4.1 **(a)** and **(b),** constancy check with ^{137}Cs standard radionuclide source over the entire period shows linearity indicating that both systems had reproducibility within the ±5% acceptable tolerance levels as required by well-established international protocols (IAEA TRS 454, 2006 and IAEA-TECDOC-602, 1991).

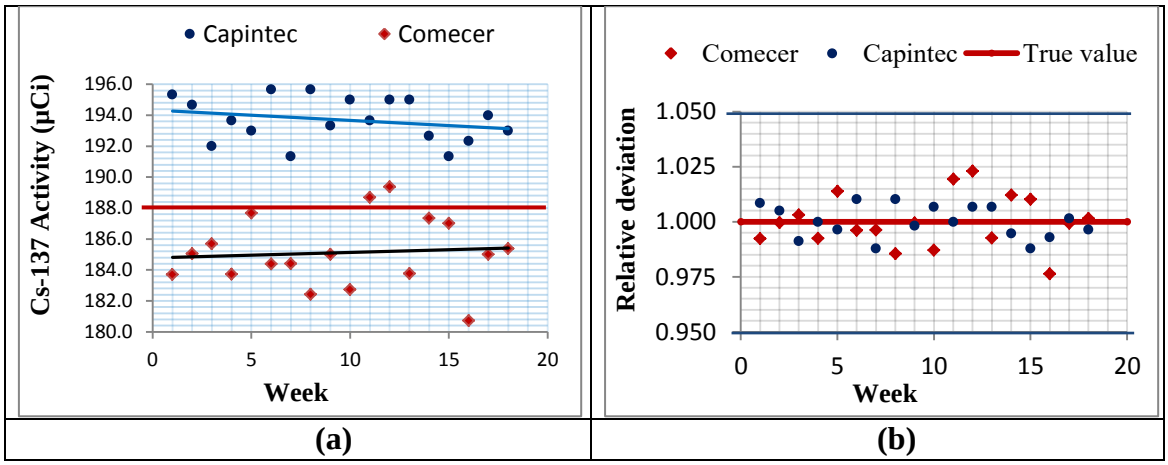


Figure 4.1**: (a)** Graph of activity against number of weeks for constancy check **(b)** Relative deviation against number of weeks for constancy check on Comecer and Capintec dose calibrators.

4.4 Relative response check

Table 4.5: Relative response to ^{137}Cs radionuclide source

^{137}Cs Activity (µCi)	**Comecer reading (µCi)**		**Capintec reading (µCi)**	
Radionuclide window	Mean	SD	Mean	SD
^{137}Cs	6.90±1.22%	0.08	7.30±4.50%	0.30
^{57}Co	12.23±0.84%	0.10	21.60±5.00%	1.10
^{99m}Tc	14.17±1.06%	0.15	29.10±5.00%	1.60
^{67}Ga	11.80±1.01%	0.12	24.40±2.50%	1.60
1^{31}I	10.33±0.65%	0.07	15.30±4.00%	0.60
^{201}Tl	7.42±8.68%	0.64	9.10±6.10%	0.60

With tolerance levels of ±5% recommended by ANSI N42.13 (2004), both systems were within acceptable limits for relative response to ^{137}Cs standard radionuclide source at ^{137}Cs, ^{57}Co, ^{99m}Tc, ^{67}Ga and ^{131}I radionuclide settings.

Comecer was found to have better reproducibility as compared to Capintec with regards to relative response at these radionuclide settings. However, it was observed that both Comecer and Capintec systems had unacceptable deviations of 8.68% and 6.10% at the ^{201}Tl radionuclide setting respectively. This could have been due to a wrong gain setting at this radionuclide setting.

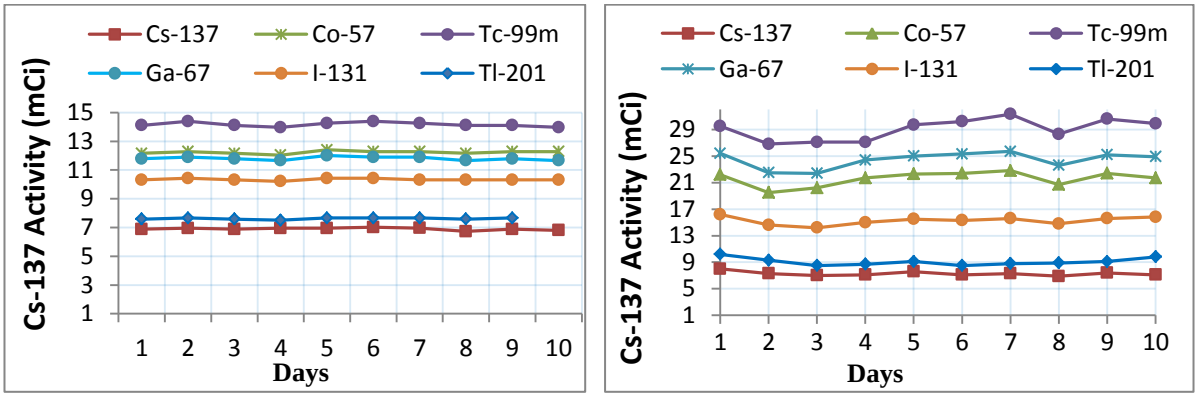


Figure 4.2: (a) Relative response test for Comecer and (b) Relative response test for Capintec using ^{137}Cs standard radionuclide source.

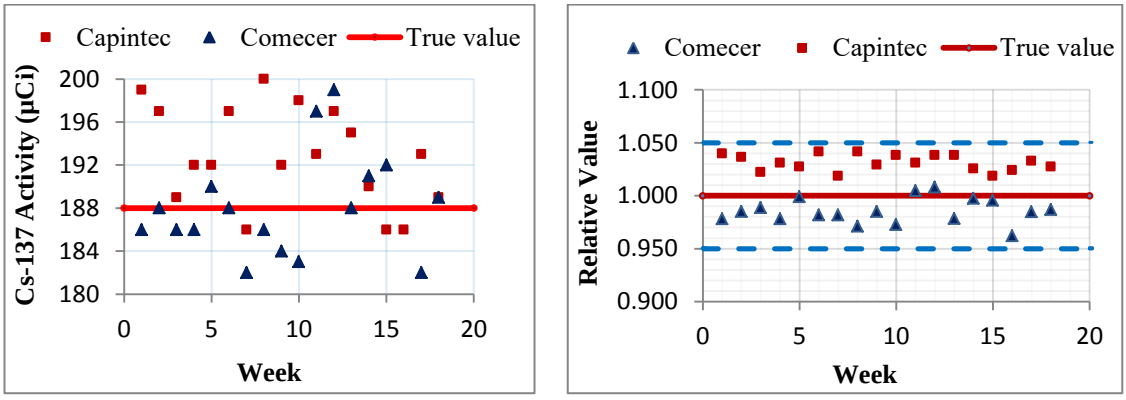
Figure 4.2 (**a**) and (**b**) above show stable readings with time for both Comecer and Capintec with regards to relative response to ^{137}Cs standards at the radionuclide settings used. This indicated that both systems have good relative response within acceptable tolerance levels.

4.5 Accuracy test

Table 4.6: Accuracy of Comecer and Capintec

Cs-137 activity (µCi)	Comecer	Capintec
Expected activity	187.8	187.8
Measured Mean activity	185.1±1.4%	193.7±3.1%

With regards to accuracy in the measurement of 187.8 µCi of ^{137}Cs standard radionuclide source over a period of 18 weeks the mean of the measured activities with the associated uncerntainties for Comecer and Capintec dose calibrators were found to be 185.1 µCi ±1.4% and 193.7 µCi ±3.1% respectivey. As seen from the results for accuracy test in Table 4.6 both dose calibrators were well within the ±5% tolerance level recommended by IAEA TRS 454 (2006).



(a) **(b)**

Figure 4.3: **(a)** Measured ^{137}Cs activities against number of weeks **(b)** Deviations of measured activity about the true activity of ^{137}Cs standard radionuclide source.

The graphs in Figure 4.3 **(a)** and **(b)** above also indicate that the accuracy in the measurement of ^{137}Cs standard radionuclide source on both Comecer and Capintec dose calibrators were well within a ±5% tolerance.

4.6 Linearity response

Table 4.7: Linearity response for Comecer to ^{99m}Tc radionuclide source

Date	Background (mCi)	Time elapsed (hrs.)	Net measured Activity(mCi)	Expected Activity(mCi)
18-11-17	0.02	0.00	773.02± 0.00%	773.02
18-11-17	0.02	2.15	602.56± 0.10%	603.01
18-11-17	0.02	6.10	380.56± 0.40%	382.07
19-11-17	0.02	18.00	97.52± 0.90%	96.63
19-11-17	0.02	24.10	48.76± 2.10%	47.75
19-11-17	0.02	30.15	24.40± 2.80%	23.74
20-11-17	0.02	36.13	12.19± 2.50%	11.89
20-11-17	0.02	40.06	7.75± 2.50%	7.56
20-11-17	0.02	42.26	6.01± 2.60%	5.86
20-11-17	0.02	48.69	2.88± 3.20%	2.79
21-11-17	0.02	67.94	0.36± 16.10%	0.31
21-11-17	0.02	74.46	0.16 ± 6.70%	0.15
22-11-17	0.02	93.94	0.017±13.20%	0.015

With tolerance levels of ±5% recommended by IAEA (TRS 454, 2006) and ANSI N42.13 (2004) for linearity test, Comecer was found to have linearity response within acceptable limits for ^{99m}Tc activities above 1mCi. For ^{99m}Tc below 1 mCi the system had unacceptable deviations and this could have been due to its low measurement resolution of 4.1 μCi (Comecer, 2010).

Comecer was found to underestimate ^{99m}Tc assays below 1 mCi by 13-16%. This agrees with Vargas et al (2018) who have reported significant underestimation of ^{99m}Tc activity by 10–20% resulting from measurements using Comecer dose

calibrators of the type VDC-405 and VDC-404. However, the activities underestimated were below the useful clinical range and as such cannot be the reason for not using Comecer for clinical assays.

Table 4.8: Linearity response for Capintec to ^{99m}Tc radionuclide source

Date	Background (mCi)	Time elapsed (hrs.)	Net measured Activity(mCi)	Expected Activity(mCi)
18-11-17	0.91	0.00	871.10±0.00%	871.10
18-11-17	0.64	2.12	676.40±0.80%	681.90
18-11-17	0.46	6.04	398.50±8.10%	433.50
19-11-17	0.65	18.04	106.50±1.80%	108.4
19-11-17	0.75	24.04	52.60±2.90%	54.19
19-11-17	0.77	30.09	26.20±2.60%	26.90
20-11-17	0.76	36.07	13.10±3.00%	13.50
20-11-17	0.71	40.00	8.37±2.30%	8.57
20-11-17	0.72	42.17	6.47±3.00%	6.67
20-11-17	0.77	48.60	3.19±0.60%	3.17
21-11-17	0.72	67.82	0.32±5.90%	0.34
21-11-17	0.78	74.30	0.17±6.30%	0.16
22-11-17	0.66	93.73	0.016±5.90%	0.017

With the tolerance level of ±5% recommended by IAEA (TRS 454, 2006) and ANSI N42.13 (2004) for linearity test, Capintec was also found to have linearity response within acceptable limits for ^{99m}Tc activities above 1 mCi.

Despite Comecers' better regression coeficient than Capintec, the study found Capintec to have better measurement resolution for activities below 1 mCi. This could have been due to its higher measurement resolution of 0.027 μCi as compared to the 4.1 μCi for Comecer system (Comecer, 2010 and Capintec, 2007).

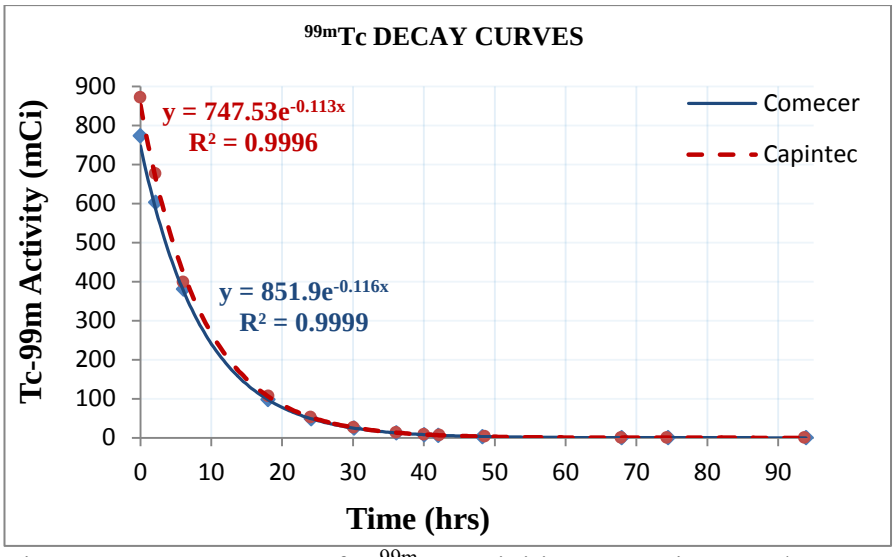


Figure 4.4: Decay curves for ^{99m}Tc activities on Capintec and Comecer

The decay curves for ^{99m}Tc both Capintec and Comecer systems were found to be exponential as expected and this was an indication the laws of radioactivity (see Figure 4.4). As also seen in Figure 4.5, both systems showed good linearity response within acceptable limits with good regression coeficients.

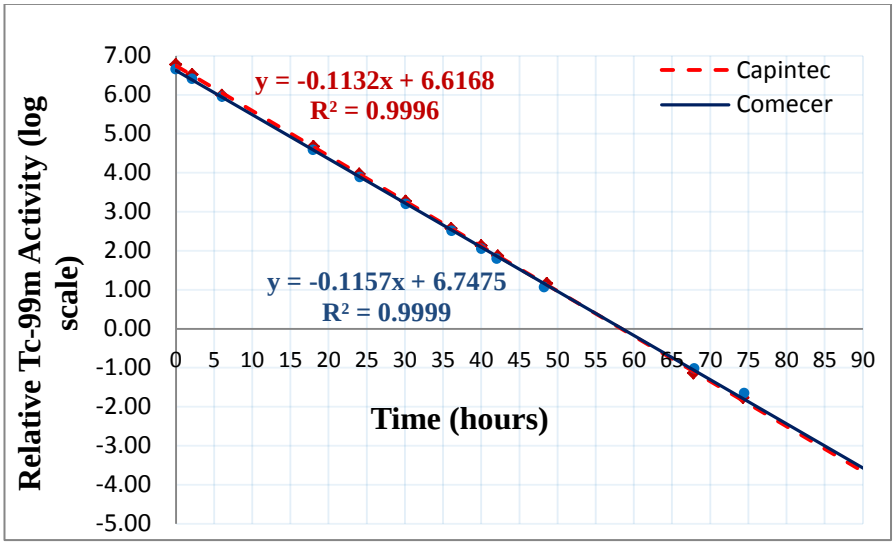
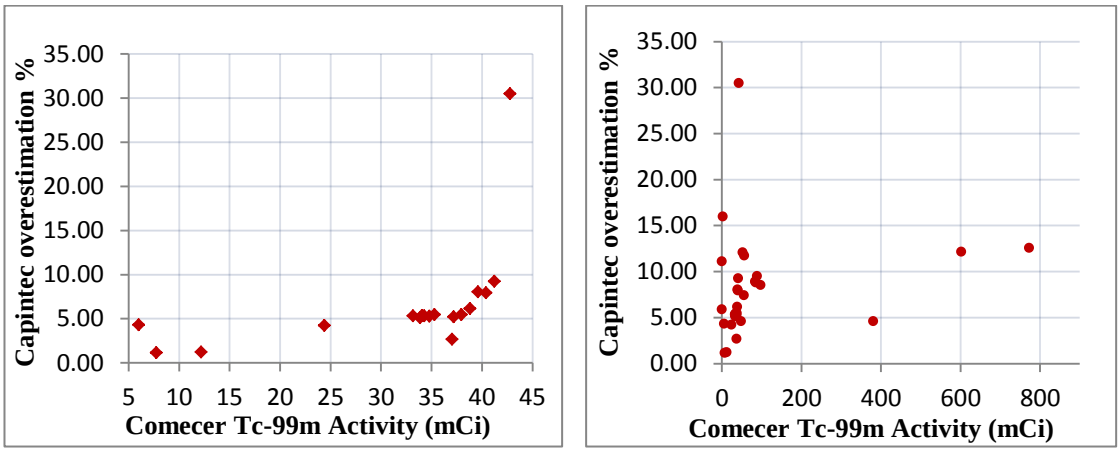


Figure 4.5: Linearity Response for Capintec and Comecer dose calibrators on logarithmic scale.

Despite showing good linearity response, the study further revealed overestimation of ^{99m}Tc assays by Capintec as shown in Figure 4.6 (a) and (b).

4.6.1 Overestimation of ^{99m}Tc assays by capintec



(a) **(b)**

Figure 4.6: **(a)** % of ^{99m}Tc activity overestimated by Capintec over entire range of activities used and **(b)** % of ^{99m}Tc activity overestimated by Capintec over useful clinical range.

From the results for linearity test, the difference between corresponding ^{99m}Tc assays with decay for Capintec and Comecer was calculated and the result was expressed as a percentage of the indicated activity for Comecer. This was the percentage of ^{99m}Tc assay overestimated by Capintec. As seen in Figure 4.6 **(a)** and **(b)** above, Capintec was found to overestimate ^{99m}Tc assays by 11-31%.

These observations led to further investigation of the effects of ion recombination and chamber residual contamination.

4.6.1 Capintec electrometer inacuracy

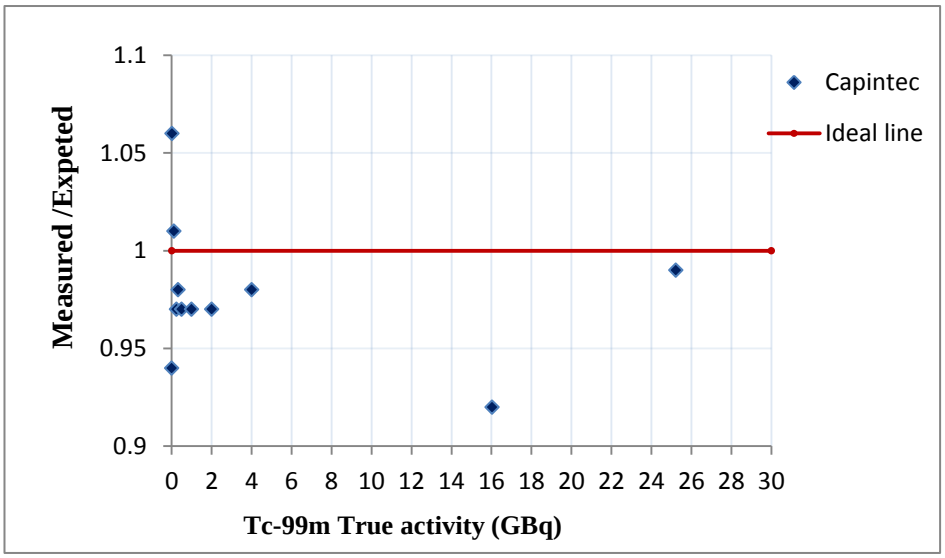


Figure 4.7: Drifts in Capintec electrometer readings

As can be seen from Figure 4.7 above, the ratio of the measured to expected activity for Capintec was found to <1 for ^{99m}Tc activities above 1 mCi. This indicated drifts in the electrometer readings for Capintec. As seen in Table 4.2 of the results for daily tests, Capintec electrometer failed to register the bias voltage for some tests. This gave a force impression of charge losses (due to ion recombination) for Capintec. This could have been the reason for unusually high background readings at the ^{99m}Tc and ^{137}Cs radionuclide settings for Capintec.

According to Gadd et al (2006), for most commercial dose calibrators, the effects of ion recombination should be less than 1% when measuring 100 GBq of ^{99m}Tc. As seen in Figure 4.7, the ratio of the indicated to true activity approached 1 for ^{99m}Tc source activities above 22 GBq and as such any recombination could have still being within the 1% tolerance.

4.6.2 **Effects liner and/or dipper residual contamination**

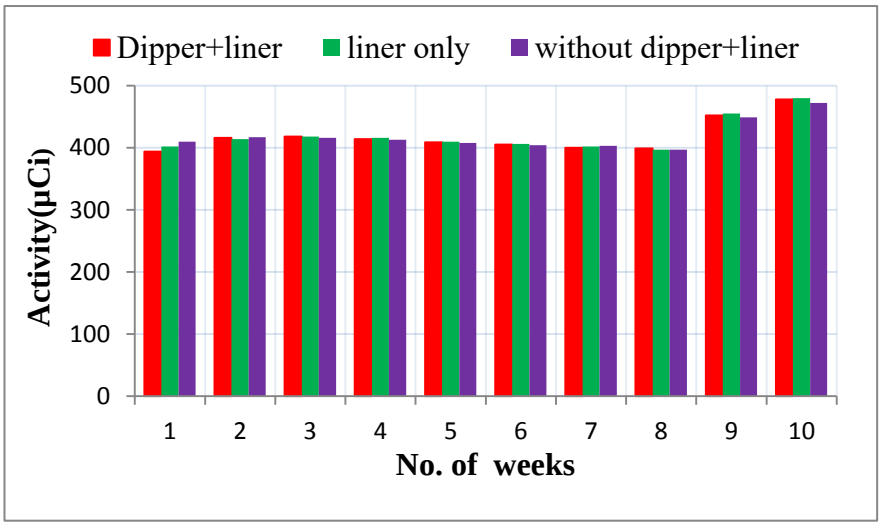


Figure 4.8: Effects of residual contamination for Capintec

Figure 4.8 above indicates that the background readings did not differ significantly with presence of liner and/or dipper. The mean of background readings with their associated standard deviations for dipper+liner, liner only and without dipper+liner configurations for Capintec at the ^{137}Cs setting were found to be 419.0±26.4 µCi, 420.0±26.6 µCi and 419.0±23.4 µCi respectively.

The dipper and liner contamination levels were calculated for each week and the results are shown in Figure 4.9 below.

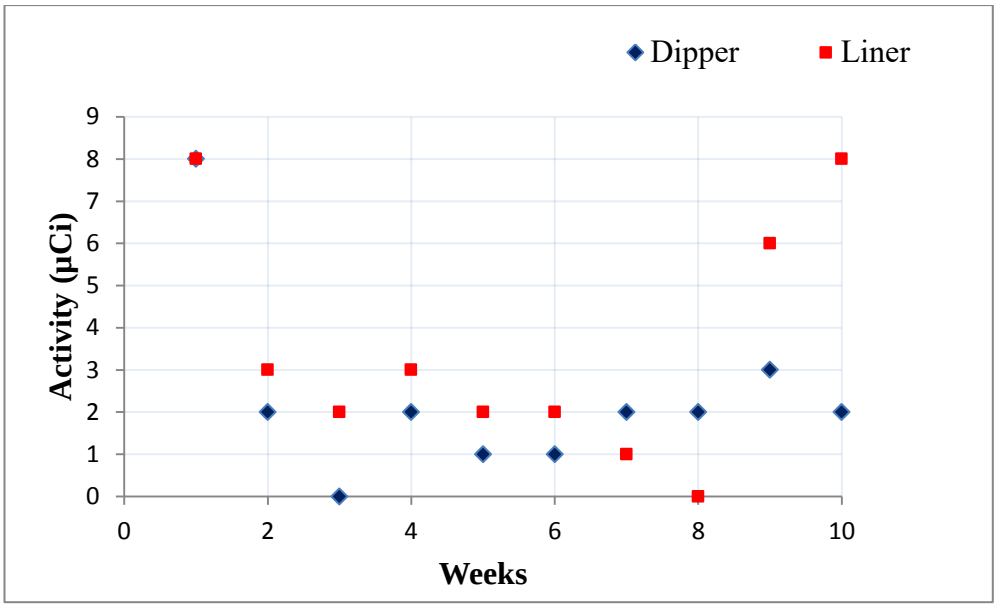


Figure 4.9: Dipper and liner contamination levels for Capintec

The liner and dipper were found to have contamination levels of 1-8µ Ci and 1-3 µCi respectively. However, these results were below Capintec acceptable background range (27-500 µCi) which indicated that residual contamination was not the reason for the usually high background at the ^{137}Cs and ^{99m}Tc radionuclide settings. The study also found non-linearity in the electronics of Capintec since the ratio of the measured response to the true response was not constant over the range of current inputs for calibrator which could have arisen from the electrometer's inherent inaccuracy. This could have led to a wrong gain at the ^{137}Cs and ^{99m}Tc radionuclide setting which gave a high background reading.

4.7 Geometry test

Table 4.9: Geometry dependence for Comecer and Capintec dose calibrators

Comecer	Activity (mCi)	10ml vial	5ml syringe	2ml syringe
	Mean Meaured	54.90±0.44%	1.76±1.68%	1.64±0.36%
	Expected	54.66	1.79	1.65
Capintec	Mean Meaured	54.98±0.51%	1.71±1.16%	1.71±0.35%
	Expected	54.70	1.73	1.72

Table 4.9 above shows the deviation of the measured from expected (decay-corrected) activities of ^{99m}Tc activity using different sample geometries. With regards to geometry dependence on Comecer the uncertainties introduced by the 10mL vial, 5mL and 2mL syringe geometry were found to be 0.44%, 1.68% and 0.36% indicating that the results were within tolerance levels.

Similarly, the influence of geometry on Capintec for the 10mL vial, 5mL and 2mL syringes used were found to be 0.51%, 1.16% and 0.35% respectively. Therefore, with the tolerance levels of ±5% recommended by well-established international protocols, both systems passed geometry test (IAEA TRS 454, 2006).

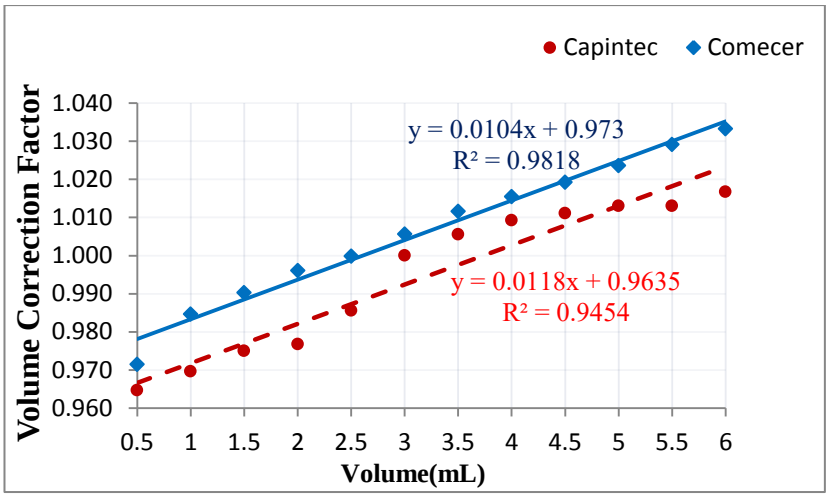


Figure 4.10: Volume correction factor against sample volume for Comecer and Capintec dose calibrators using a 10ml vial.

With regards to volume correction factors (VCF) for the 10ml vial, both calibrators had factors within the recommended 0.95<VCF<1.05 (IAEA TRS 454, 2006).

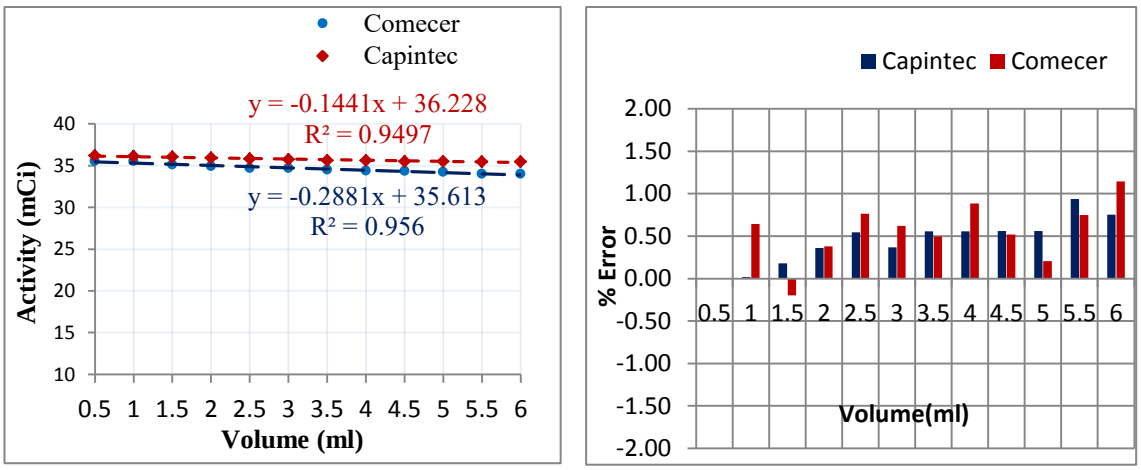


Figure 4.11: (a) Activity against source volume for vial (b) Error due to volume of source in vial.

Despite Comecer showing better geometry dependence than Capintec for the 10ml vial it was found to be more sensitive to source volume variations as compared to Capintec.

Table 4.10: Further vial geometry test for Comecer and Capintec

Dose calibrator	**Comecer**		**Capintec**	
Volume(mL)	Activity(mCi)	VCF	Activity(mCi)	VCF
0.5	35.56	1.024	36.22	1.014
1.0	35.54	1.024	36.13	1.011
1.5	35.14	1.012	36.03	1.008
2.0	34.94	1.007	35.95	1.006
2.5	34.71	1.000	35.83	1.003
3.0	34.71	1.000	35.73	1.000
3.5	34.51	0.994	35.62	0.997
4.0	34.39	0.991	35.62	0.997
4.5	34.37	0.990	35.53	0.994
5.0	34.23	0.986	35.52	0.994
5.5	34.01	0.980	35.47	0.993
6.0	34.01	0.980	35.47	0.993
Mean	34.68±1.47%		35.76±0.71%	
SD	0.51		0.26	

A further investigation of the influence of vial geometry on the assayed ^{99m}Tc activity using Comecer and Capintec was done over a period of 9minutes. Since this time was much shorter than the 6hrs half-life for ^{99m}Tc, the standard deviation was calculated to check the deviation of activity with sample volume on the two calibrators. The standard deviations for Comecer and Capintec were found to be 1.47% and 0.71% respectively. This also confirmed that both systems were within the ±2% tolerance stipulated by the National Physical Laboratory (Gadd et al, 2006).

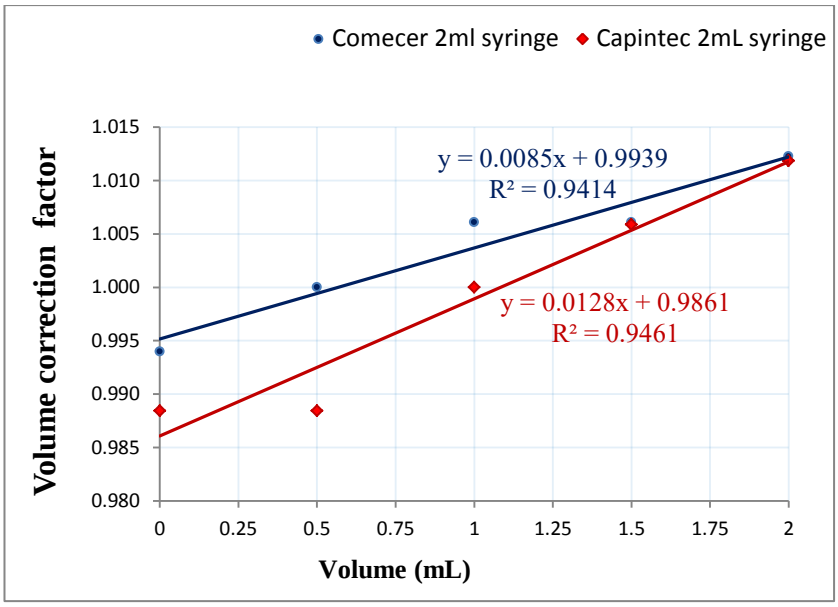


Figure 4.12: VCF against sample volume for the 2ml syringe.

Volume correction factors were also determined for both systems using the 2ml syringe which is normally assayed before injecting into patients.

According to IAEA TRS 454 (2006), new volume correction factors (VCF) must be determined when the influence of geometry is >5%. In addition to both calibrators passing this test, VCFs were determined and it was revealed that both systems had factors within the acceptable range of 0.95<VCF<1.05 (see Figure 4.12 above).

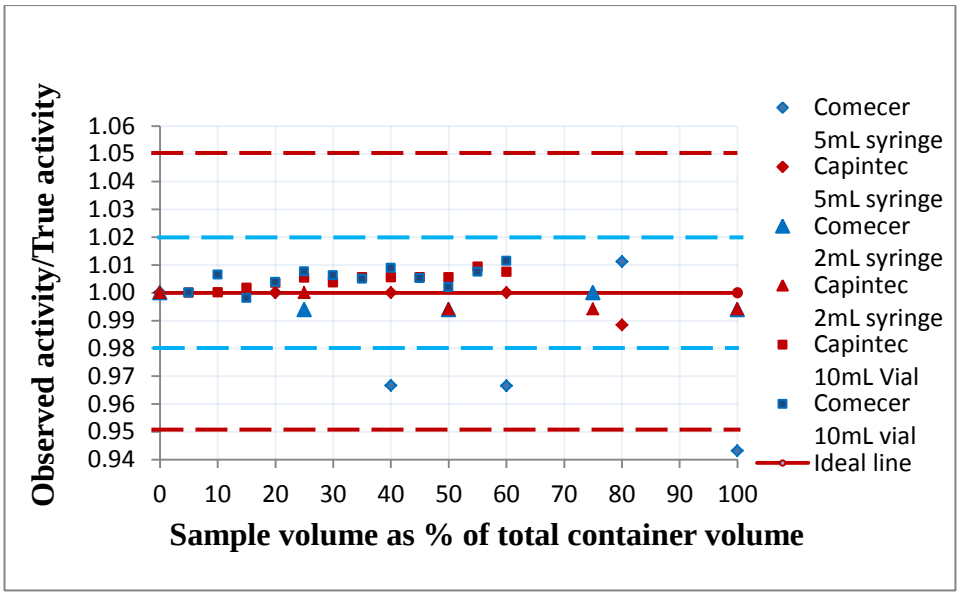


Figure 4.13: The influence of Source container and sample volume on assayed ^{99m}Tc activity within 2 percent and 5 percent uncertainties.

The overall influence of source container and sample volume geometry was investigated by normalizing each observed measurement to its true activity and plotting it against the sample volume as a percentage of the total container volume.

It was observed that for the 10ml vial and 2 ml syringe both Comecer and Capintec system had geometry dependence within 2%. However, for the 5ml syringe only Capintec was within 2% deviation while Comecer was found to be within 5% limit with regards to geometry dependence. These results also showed that Capintec was less sensitive to container and source volume geometry variations.

4.8 CHOOSING REFERENCE DOSE CALIBRATOR FOR CROSS CALIBRATION

The reference dose calibrator for cross-calibration was chosen based on results from daily performance checks, linearity, geometry and accuracy tests on Comecer and Capintec dose calibrators using ^{131}I, ^{99m}Tc and ^{137}Cs Certified radioactivity standard sources.

Table 4.11: Measurement accuracy with Comecer dose calibrator

Source	Calibration date and activity (mCi)		Expected activity (mCi) and date		Measured activity(mCi)
^{131}I	14-09-17	168.00	100.00	20-09-17	105.80±0.06%
^{131}I	14-09-17	33.60	20.00	20-09-17	20.10±0.50%
^{99m}Tc	28-09-17	1411.87	1071.17	26-10-17	1070.33±0.08%
^{137}Cs	13-10-05	0.25	0.19	26-10-17	0.20±0.05%

Table 4.12: Measurement accuracy with Capintec dose calibrator

Source	Calibration date and activity(mCi)		Expected activity(mCi) and date		Measured activity(mCi)
^{99m}Tc	28-09-17	1412.00	1071.17	26-10-17	1198.37±11.8%
^{137}Cs	13-10-05	0.25	0.19	26-10-17	0.355±86.84%

With the tolerance level of ±10% recommended by IAEA TRS 454 (2006) results for the measurements of ^{131}I, ^{99m}Tc and ^{137}Cs calibrated sources; it was observed that only Comecer system was well within acceptable deviation. Capintec was found to have unacceptable deviations of 11.87% and 86.84% with regards to assay accuracy of ^{99m}Tc and ^{137}Cs calibrated sources respectively. This could have been due to the unusually high background observed at the ^{99m}Tc and ^{137}Cs settings for Capintec.

These deviations could have also been due to drifts in the electronics for Capintec (electrometer's failure to register bias voltage) or as a result of errors in the dial settings leading to undesired gain. Based on these observations and assay accuracy of ^{131}I, ^{99m}Tc and ^{137}Cs calibrated sources, Comecer were chosen as the reference dose calibrator for the cross-calibration.

4.8.1 ^{137}Cs Calibration factor (CF)

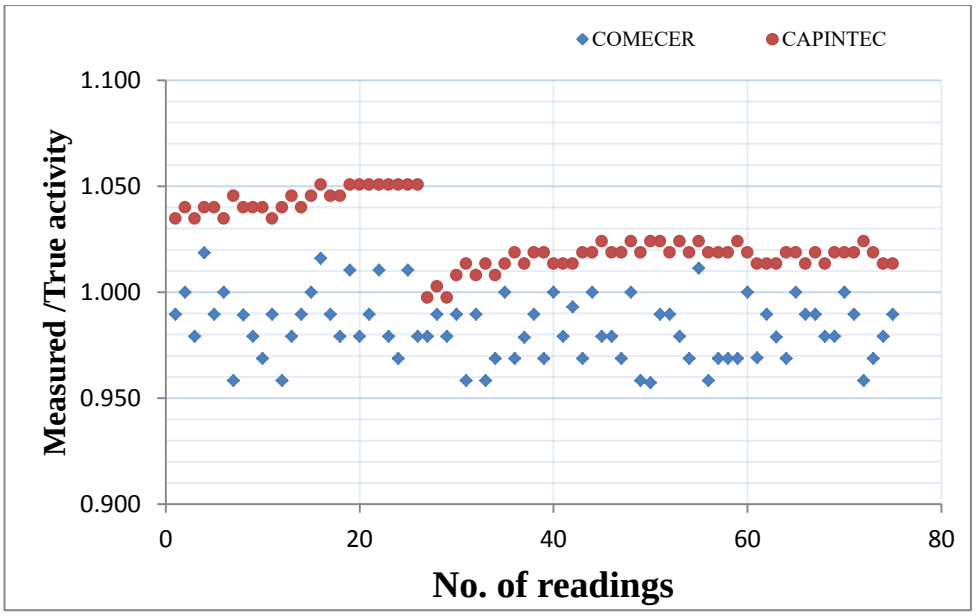


Figure 4.14: Normalized ^{137}Cs activity against number of reading within 5% error margin.

The results were normalized to the decay-corrected activity of ^{137}Cs standard radionuclide source. The activity of ^{137}Cs with Comecer was divided by that of Capintec to obtain a calibration factor (CF) for each measurement.

The mean of ^{137}Cs calibration factors with its associated standard deviation on Capintec with Comecer as the reference dose calibrator was found to be 0.95±0.017.

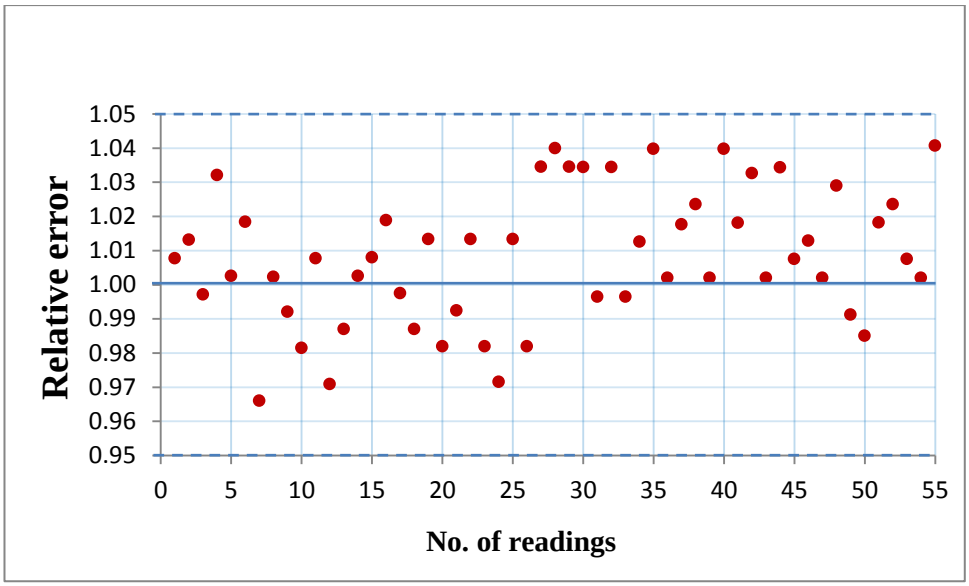


Figure 4.15: Error due to ^{137}Cs calibration factor.

The determined calibration factor (CF) for ^{137}Cs was used to calculate the true activity of Capintec using the equation;

$$\text{True activity} = \text{CF} \times \text{Measured activity}$$

As seen in Figure 4.15 above the all the results obtained using the determined calibration factor was found to be within 5% deviation. Therefore, the CF for ^{137}Cs standard radionuclide source on Capintec was found to be practically valid.

4.9 Cross-calibration curve for ^{99m}Tc assays on Capintec with Comecer as the reference dose calibrator.

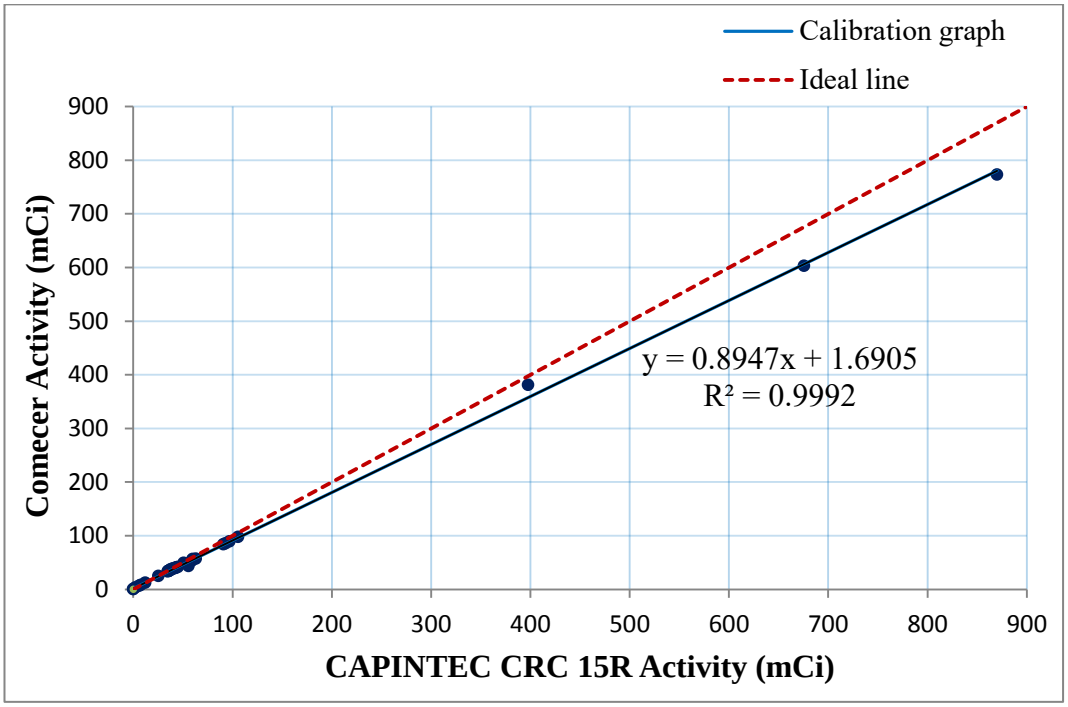


Figure 4.16: Calibration curve for Capintec with Comecer as reference dose calibrator over entire range of ^{99m}Tc source activities used.

A calibration curve for ^{99m}Tc assays on Capintec was obtained using Comecer as the reference dose calibrator. An ideal line for which both calibrators give the same reading for ^{99m}Tc source activity was also plotted to investigate the deviation of the calibration curve from the ideal case over the entire range of ^{99m}Tc activities used.

The calibration equation of Capintec with Comecer as the reference dose calibrator over the entire range (0.016-773.02 mCi) of ^{99m}Tc activities used for the study was found to be Capintec = 0.8947×Comecer + 1.6905 and this had a good regression coefficient $R^2 = 0.9992$.

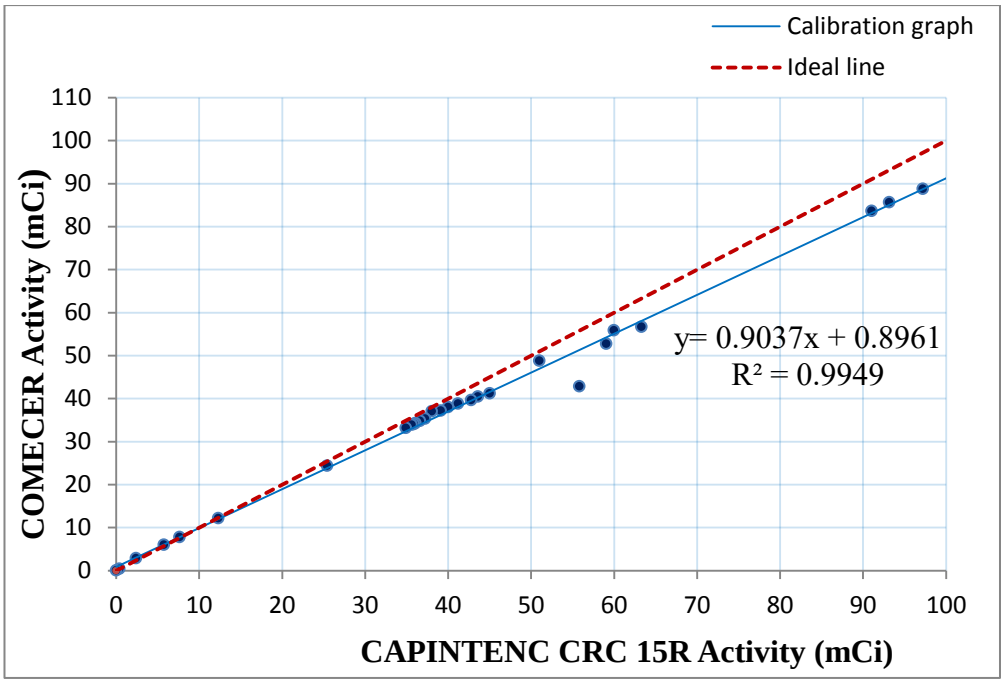


Figure 4.17: Calibration curve for Capintec with Comecer as reference dose calibrator over useful clinical range of ^{99m}Tc source activities.

A calibration curve was also obtained for ^{99m}Tc source activities within the useful clinical range. The calibration equation of Capintec using Comecer as the reference dose calibrator over the useful clinical range was found to be Capintec = 0.9037×Comecer + 0.8961 with excel and Comecer = 1.69051 + 0.894665 Capintec with Minitab. As seen from Figure 4.16 and Figure 4.17 above, the calibration curve approached the ideal line for ^{99m}Tc source activities below 25mCi. The deviation of the calibration curve from the ideal line was therefore greater for higher ^{99m}Tc activities.

4.9.1 Validation of ^{9m}Tc calibration curve

From the summary of the regression analysis in Appendix B.2a, R^2 =0.999326934 and the P-values for the independent variable and intercept were 2.297×10^{-44} and 0.039194 respectively. These indicated that there is no significant influence of external factors on the independent variable and the intercept for the developed model. Therefore the model can be used to predict Capintec activity with Comecer as reference dose calibrator at 95% confidence level. Practically the model was also validated by measuring ^{99m}Tc activities at different time intervals. The expected activity (predicted with Comecer) and theoretical activity (calculated with the calibration equation) for ^{99m}Tc assays were compared for the calibration curve developed with Excel and Minitab (Table 4.13 and Table 4.14).

Table 4.13: Excel validation of ^{99m}Tc calibration

Capintec	Comecer	Theoretical
534.00	476.00	479.46±0.73%
431.00	389.00	387.31±0.44%
301.00	273.00	271.00±0.73%
244.00	222.00	220.00±0.90%
113.00	104.00	102.79±1.16%
91.00	83.00	83.11±0.13%
69.00	64.00	63.42±0.90%
14.00	14.00	14.22±1.55%

Table 4.14: Minitab validation of ^{99m}Tc calibration

Capintec	Comecer	Theoretical
534.00	476.00	479.44±0.72%
431.00	389.00	387.29±0.44%
301.00	273.00	270.98±0.74
244.00	222.00	219.99±0.91%
113.00	104.00	102.79±1.17%
91.00	83.00	83.11±0.13%
69.00	64.00	63.42±0.90%
14.00	14.00	14.22±1.54%

As shown in Table 4.13 and Table 4.14, practical validation of ^{99m}Tc calibration using Excel and Minitab were found to be within deviations of 2% . Therefore, the calibration equation or curve can be used to calculate the correct ^{99m}Tc activity of Capintec with Comecer as the reference dose calibrator.

4.10 Determination of new dial value (N_A) for ^{99m}Tc and ^{137}Cs on Capintec

Based on the unusually background reading observed at the ^{99m}Tc and ^{137}Cs and the electrometers' failure to register the correct biasing voltage (see Table 4.2), new dial values were determined for Capintec to adjust the gain of the electrometer so that its measurements could be traceable to primary standards for ^{99m}Tc and ^{137}Cs certified radionuclide sources. The new dial values on Capintec were determined using a modified equation of the gain equation (2.3.8) given by Capintec (2007).

The modified equation was given by;

$$\text{New } N_A = \frac{\frac{\text{Old } N_A}{1076} + 0.08}{\frac{\text{Expected Actity}}{\text{Measured Activity}} + 0.08} \qquad (4.9.1)$$

4.10.1 ^{99m}Tc new dial value (N_A) on Capintec

Table4.15: Old and new dial value for ^{99m}Tc on Capintec

Old N_A	Measured	Expected	New N_A
80	676.40±12.20%	603.01	100
80	398.50±4.30%	382.07	87
80	106.50±10.20%	96.63	97
80	52.60±10.20%	47.75	97
80	26.20±10.40%	23.74	97
80	13.10±10.20%	11.89	97
80	8.37±10.70%	7.56	98
80	6.47±10.40%	5.86	97
80	0.32±3.2%	0.31	85
80	0.016±6.70%	0.015	91
		Mean	95 ±5

As seen from Table 4.15, the dial value N_A = 80 supplied by Capintec for ^{99m}Tc gave assay accuracy within 3.20-12.20%.

Using equation (4.9.1), the theoretical dial value for ^{99m}Tc on Capintec was found to be N_A = 95±5. This dial value was validated practically to determine its useful clinical range within the manufacturing tolerance. This involved adjusting the electrometer displayed dial value within the theoretical range (90-100) until the display indicated the true activity of ^{99m}Tc certified source within ±3% tolerance (Capintec 2007, 1990).

Table 4.16: Practical range of ^{99m}Tc dial value on Capintec

	New N_A	Measured	Expected	Measured	Expected
	94	82.0±1.0%	81.2	42.2±2.0%	41.3
	95	82.1±0.7%	81.5	42.0±2.0%	41.3
	96	80.8±0.5%	80.4	41.7±1.0%	42.2
	97	80.8±0.5%	80.4	41.4±2.0%	42.3
	98	80.9±0.7%	81.5	41.6±2.0%	42.3
Mean	96±2				

The new dial value for ^{99m}Tc on Capintec was found to be practically valid for $N_A = 96 \pm 2$. This gave assay accuracy within ±2%.

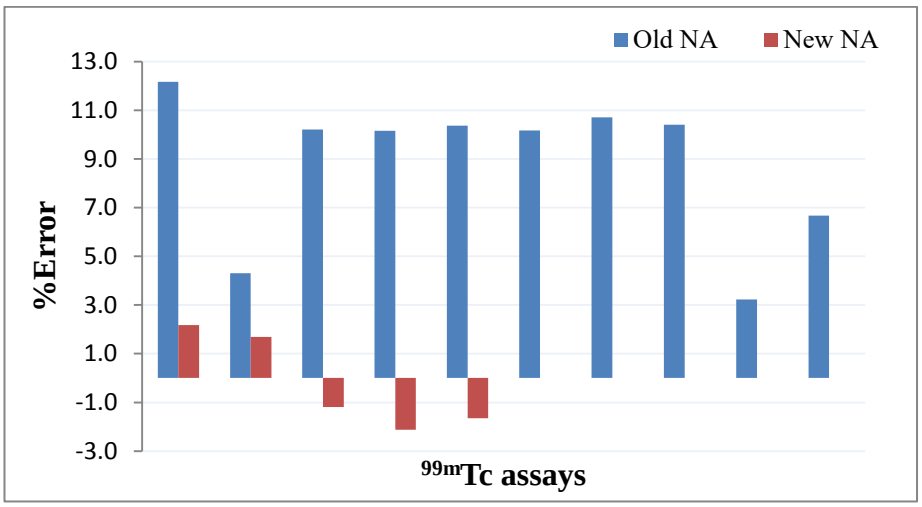


Figure 4.18: Error due to old and New dial values for ^{99m}Tc assays on Capintec.

With this practical dial value of $N_A = 96 \pm 2$ the uncertainty in ^{99m}Tc assays on Capintec was found to be within 0.5-2% as compared to the 3.20-12.20% with dial value $N_A = 80$ supplied by Capintec. Therefore, with the calculated dial value the agreement between the calculated and observed responses for Capintec fell within the ±3% manufacturing tolerance as required by Capintec (Capintec 2007, 1990).

4.10.2 ^{137}Cs dial value (N_A) on Capintec

The dial value for ^{137}Cs on Capintec was also determined and practically validated. As shown in Table 4.17, with dial value N_A = 220 supplied by Capintec for ^{137}Cs assays the drift in the gain setting gave large uncertainties within 133-137%. The theoretically determined dial value for ^{137}Cs was found to be $N_A = 628 \pm 7$.

Table 4.17: New dial value for ^{137}Cs on Capintec

Old N_A	Measured	Expected	New N_A
220	434±133%	187	626
220	434±133%	187	626
220	432±132%	187	623
220	432±132%	187	623
220	436±134%	187	629
220	428±129%	187	616
220	434±133%	187	626
220	435±133%	187	627
220	443±137%	187	641
220	445±138%	187	644
220	434±133%	187	626
220	437±134%	187	631
220	438±135%	187	632
220	435±133%	187	627
		Mean	628±7

This theoretically determined dial value was validated practically to determine its useful clinical range and the uncertainty involved by assaying a known activity of ^{137}Cs while adjusting the dial value within its theoretical range (621-635).

Table 4.18: Practical range of ^{137}Cs dial value

	New N_A	Measured	Expected
	620	188 ±0.5	187
	621	188±0.5%	187
	622	187±0.0%	187
	623	187±0.0%	187
	624	186±0.5%	187
	624	186±0.5%	187
	625	186±0.5%	187
	626	186±0.5%	187
	627	186±0.5%	187
	628	186±0.5%	187
	629	185±1.1%	187
	630	185±1.1%	187
	631	185±1.1%	187
	632	184±1.6%	187
	633	184±1.6%	187
Mean	626±4		

The theoretically determined dial value for ^{99m}Tc on Capintec was found to be practically valid for $N_A = 626 \pm 4$.With this practical dial value the uncertainty in assay of ^{137}Cs standard radionuclide source with Capintec was within 0.5-1.6% as compared to the 133-137% with dial value supplied by Capintec.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Performance evaluation and cross-calibration have been done on Capintec and Comecer radionuclide dose calibrators. The study has revealed variations in the performance of both systems within recommended tolerance levels. Both systems passed constancy, relative response and accuracy tests using ^{137}Cs standard radonuclide source within acceptable limits stipulated by IAEA and ANSI. With tolerance levels recommended by IAEA for linearity response and geometry dependence with ^{99m}Tc source activity, both systems were also found to be within tolerance levels.

However, the study revealed significant overestimation and underestimation of ^{99m}Tc assays by Capintec and Comecer sytems respectively. The study found drifts in the electronics of Capintec system to be the reason for the unusually high background readings at ^{99m}Tc and ^{137}Cs radionuclide settings. However, a calibration curve/equation and new dial values for ^{99m}Tc and ^{137}Cs have been determined to ensure effective use of the system.

5.1.1 Recommendations

Based on the results of the study, the following recommendations are being made to the Nuclear Medicine Department, the Nuclear Regulatory Authority and the Research Community:

5.1.2 Nuclear Medicine Department

It is recommended that purchase of more standard radionuclide sources (^{133}Ba and ^{57}Co) be done for further checks of the accuracy of the calibrators over the entire range of energies since only ^{137}Cs standard radionuclide source is currently available. It is also recommended that an instrument log book should be introduced and Medical Physicists engaged to supervise the performance of daily constancy, quarterly linearity and annual tests to ensure optimal performance and usage of the dose calibrators. Due to drifts in the electronics of Capintec dose calibrator, it is recommended that the determined Cross-calibration curve/equation and the new dial values for ^{99m}Tc and ^{137}Cs be used for Capintec system until an electronic check-up is done.

5.1.3 Nuclear Regulatory Authority and Radiation Protection Institute

There is need for the provision of proper regulatory performance standards in order to ensure strict adherence to quality control tests at internationally recommended frequencies. A Radiation Safety officer should also be actively engaged over the radionuclide sources and equipment. There is need for ensuring that dose calibrators are rigorously maintained to meet the national requirements set by the Nuclear Regulatory Authority.

5.1.4 Research Community

It is recommended that further research be undertaken to assess the performance of both dose calibrators with the use of other radionuclide sources such ^{133}Ba, ^{57}Co and ^{131}I. There is also need for further work on the electrometers' inherent inaccuracy, linearity, range changing and the effects of ion recombination for 30 to 100 GBq of ^{99m}Tc source activities.

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APPENDIX

APPENDIX A: PERFORMANCE EVALUATION

Days	Auto zero (mV)	Background (µCi)	High voltage test (V)	Data check Cs-137 (µCi)
1	0.05	67.40	0.10	197.00
2	0.04	36.90	0.15	201.00
3	-0.05	58.30	0.00	197.00
4	0.05	55.50	162.80	191.00
5	0.05	56.90	0.00	191.00
6	-0.05	59.60	162.60	189.00
7	0.04	60.30	162.80	190.00
8	0.05	53.50	162.80	197.00
9	0.05	54.00	162.80	189.00
10	0.05	44.40	162.80	183.00
11	0.05	50.10	162.80	187.00
12	0.05	45.40	162.90	189.00
13	0.05	45.00	0.15	190.00
14	0.05	56.00	162.60	191.00
15	0.05	50.40	162.80	196.00
Mean	0.049 ±0.0035	52.90 ±7.72		191.87 ±4.75%

A.1b	**Daily quality control on Comecer dose calibrator**		
Days	Background (µci)	Data check (µCi)	% Deviation
1	19.00	185.53±	-0.79
2	20.00	187.48	0.26
3	20.00	183.58	-1.83
4	20.00	190.98	2.13
5	20.00	185.53	-0.79
6	20.00	187.48	0.26
7	20.00	179.67	-3.92
8	20.00	185.48	-0.81
9	20.00	191.39	2.35
10	25.00	183.58	-1.83
11	19.00	185.53	-0.79
12	20.00	185.53	-0.79
13	20.00	183.58	-1.83
14	20.00	185.53	-0.79
15	20.00	189.44	1.30
	20.20 ±8.61%	191.87±1.62%	

A.2a	**Constancy check on Comecer**				
	Cs-137 Activity(μCi)				
Week	Background	R1-B	R2-B	R3-B	R_{ave}
1	11.6	186.0	183.5	181.6	183.7
2	13.8	188.0	179.7	187.5	185.1
3	11.6	186.2	185.5	185.5	185.7
4	9.7	186.1	179.7	185.5	183.7
5	13.8	190.0	189.4	183.6	187.7
6	13.8	188.2	183.6	181.6	184.4
7	11.6	182.3	181.6	189.6	184.4
8	13.8	186.1	181.6	179.7	182.4
9	11.6	184.2	189.4	181.6	185.0
10	13.7	183.3	183.6	181.6	182.7
11	23.4	197.0	187.5	181.6	188.7
12	17.6	199.0	181.6	187.5	189.4
13	13.7	188.1	181.6	181.7	183.8
14	7.8	191.0	185.5	185.5	187.4
15	7.8	192.0	185.5	183.5	187.0
16	19.5	177.2	183.6	181.6	180.7
17	21.5	182.1	185.5	187.5	185.0
18	9.7	189.0	183.6	183.6	185.4
			Mean	185.1±1.2%	
			SD	2.2	

A.2b Constancy check Capintec

Cs-137 Activity(μCi)					
Week	Background (B)	R1-B	R2-B	R3-B	R_{ave}
1	457.0	199.0	190.0	197.0	195.3
2	381.0	197.0	189.0	198.0	194.7
3	419.0	189.0	190.0	197.0	192.0
4	522.0	192.0	191.0	198.0	193.7
5	565.0	192.0	190.0	197.0	193.0
6	568.0	197.0	191.0	199.0	195.7
7	481.0	186.0	191.0	197.0	191.3
8	435.0	200.0	190.0	197.0	195.7
9	522.0	192.0	190.0	198.0	193.3
10	378.0	198.0	190.0	197.0	195.0
11	368.0	193.0	191.0	197.0	193.7
12	412.0	197.0	191.0	197.0	195.0
13	303.0	195.0	192.0	198.0	195.0
14	154.0	190.0	191.0	197.0	192.7
15	262.0	186.0	191.0	197.0	191.3
16	292.0	186.0	192.0	199.0	192.3
17	333.0	193.0	191.0	198.0	194.0
18	177.0	189.0	192.0	198.0	193.0
				Mean	193.7±0.74
				SD	1.4

A.3a	**Relative response test Capintec**					
	Activity(MBq)					
Weeks	Cs-137	Co-57	Tc-99m	Ga-67	I-131	Tl-201
1	8.00	22.20	29.50	25.40	16.20	10.20
2	7.30	19.50	26.80	22.50	14.60	9.30
3	7.00	20.20	27.10	22.40	14.20	8.50
4	7.10	21.70	27.10	24.40	15.00	8.70
5	7.60	22.30	29.70	25.00	15.50	9.10
6	7.10	22.40	30.20	25.30	15.30	8.50
7	7.30	22.80	31.30	25.70	15.60	8.80
8	6.90	20.70	28.30	23.60	14.80	8.90
9	7.40	22.40	30.60	25.20	15.60	9.10
10	7.10	21.70	29.90	24.90	15.80	9.80
Mean	7.30	21.60	29.10	24.40	15.30	9.10
SD	0.30	1.10	1.60	1.60	0.60	0.60
%Error	4.50	5.10	5.50	2.50	4.00	6.10

A.3b	**Relative response test Comecer**					
	Activity(MBq)					
Weeks	Cs-137	Co-57	Tc-99m	Ga-67	I-131	Tl-201
1	6.88	12.16	14.11	11.78	10.31	7.59
2	6.95	12.28	14.39	11.89	10.42	7.66
3	6.88	12.16	14.11	11.78	10.31	7.59
4	6.95	12.04	13.97	11.66	10.21	7.51
5	6.95	12.41	14.25	12.01	10.42	7.66
6	7.02	12.28	14.39	11.89	10.42	7.66
7	6.96	12.28	14.25	11.89	10.31	7.66
8	6.73	12.16	14.11	11.66	10.31	7.59
9	6.88	12.28	14.11	11.78	10.31	7.66
10	6.81	12.28	13.97	11.66	10.31	5.59
Mean	6.90	12.23	14.17	11.80	10.33	7.42
SD	0.08	0.10	0.15	0.12	0.07	0.64
%Deviation	1.22	0.84	1.06	1.01	0.65	8.68

A.4a		**Accuracy test Comecer**				
		Cs-137 Activity (µCi)				
Week	Background B	R1-B	R2-B	R3-B	R_{ave}	Expected
1	11.6	186.0	183.5	181.6	183.7	189.0
2	13.8	188.0	179.7	187.5	185.1	189.0
3	11.6	186.0	185.5	185.5	185.7	189.0
4	9.7	186.0	179.7	185.5	183.7	189.0
4	13.8	190.0	189.4	183.6	187.7	189.0
6	13.8	188.0	183.6	181.6	184.4	189.0
7	11.6	182.0	181.6	189.6	184.4	189.0
8	13.8	186.0	181.6	179.7	182.4	189.0
9	11.6	184.0	189.4	181.6	185.0	189.0
10	13.7	183.0	183.6	181.6	182.7	189.0
11	23.4	197.0	187.5	181.6	188.7	189.0
12	17.6	199.0	181.6	187.5	189.4	186.0
13	13.7	188.0	181.6	181.7	183.8	186.0
14	7.8	191.0	185.5	185.5	187.4	186.0
15	7.8	192.0	185.5	183.5	187.0	186.0
16	19.5	177.0	183.6	181.6	180.7	186.0
17	21.5	182.0	185.5	187.5	185.0	186.0
18	9.7	189.0	183.6	183.6	185.4	186.0
				Mean	185.1±1.4%	187.8

A.4b	**Accuracy test Capintec**					
	Cs-137 Activity (μCi)					
Week	Background B	R1-B	R2-B	R3-B	R_{ave}	Expected
1	457.0	199.0	190.0	197.0	195.3	189.0
2	381.0	197.0	189.0	198.0	194.7	189.0
3	419.0	189.0	190.0	197.0	192.0	189.0
4	522.0	192.0	191.0	198.0	193.7	189.0
5	565.0	192.0	190.0	197.0	193.0	189.0
6	568.0	197.0	191.0	199.0	195.7	189.0
7	481.0	186.0	191.0	197.0	191.3	189.0
8	435.0	200.0	190.0	197.0	195.7	189.0
9	522.0	192.0	190.0	198.0	193.3	189.0
10	378.0	198.0	190.0	197.0	195.0	189.0
11	368.0	193.0	191.0	197.0	193.7	189.0
12	412.0	197.0	191.0	197.0	195.0	186.0
13	303.0	195.0	192.0	198.0	195.0	186.0
14	154.0	190.0	191.0	197.0	192.7	186.0
15	262.0	186.0	191.0	197.0	191.3	186.0
16	292.0	186.0	192.0	199.0	192.3	186.0
17	333.0	193.0	191.0	198.0	194.0	186.0
18	177.0	189.0	192.0	198.0	193.0	186.0
				Mean	193.7±3.1%	187.8

A.5a	**Linearity response test for Comecer**		
Date	Background B (mCi)	Time	Measured-B Activity(mCi)
18-11-17	0.02	13:08	773.02
18-11-17	0.03	15:17	602.56
18-11-17	0.03	19:14	380.56
19-11-17	0.02	07:11	97.52
19-11-17	0.02	13:11	48.76
19-11-17	0.02	19:14	24.4
20-11-17	0.02	01:13	12.19
20-11-17	0.02	05:09	7.75
20-11-17	0.02	07:21	6.01
20-11-17	0.02	13:47	2.88
21-11-17	0.02	09:27	0.36
21-11-17	0.02	16:29	0.19
22-11-17	0.02	11:31	0.017

A.5b	**Linearity response test for Capintec**		
Date	Background(mCi)	Time	Measured-B Activity(mCi)
18-11-17	0.91	13:10	871.1
18-11-17	0.64	15:20	676.4
18-11-17	0.46	19:16	298
19-11-17	0.65	07:14	106.5
19-11-17	0.75	13:15	52.6
19-11-17	0.77	19:16	26.2
20-11-17	0.76	01:16	13.1
20-11-17	0.71	05:11	8.37
20-11-17	0.72	07:24	6.47
20-11-17	0.77	13:49	3.09
21-11-17	0.72	09:27	0.31
21-11-17	0.78	16:00	0.173
22-11-17	0.66	11:33	0.016

A.5c	**Contamination test for Capintec**		
	Background activity at Cs-137 setting (μCi)		
Weeks	With Dipper+liner	liner only	without dipper+liner
1	394.0	402.0	410.0
2	416.0	414.0	417.0
3	418.0	418.0	416.0
4	414.0	416.0	413.0
5	409.0	410.0	408.0
6	405.0	406.0	404.0
7	400.0	402.0	403.0
8	399.0	397.0	397.0
9	452.0	455.0	449.0.0
10	478.0	480.0	472.0
Mean	419.0±6.3%	420.0±6.3%	419.0±5.6%
SD	26.4	26.6	23.4

A.6a	**2ml Syringe geometry dependence on Comecer**			
Volume(mL)	Time	Measured Activity(mCi)	Expected Activity(mCi)	VCF
0.0	14:35	1.66	1.66	0.994
0.5	14:37	1.65	1.66	1.000
1.0	14:39	1.64	1.65	1.006
1.5	14:41	1.64	1.64	1.006
2.0	14:43	1.63	1.64	1.012
Mean		1.64±0.36%	1.65	

A.6b	**2ml Syringe geometry dependence on Capintec**			
Volume(mL)	Time	Measured Activity(mCi)	Expected Activity(mCi)	VCF
0.0	14:36	1.73	1.73	0.988
0.5	14:37	1.73	1.73	0.988
1.0	14:40	1.71	1.72	1.000
1.5	14:42	1.70	1.71	1.006
2.0	14:44	1.69	1.70	1.012
Mean		1.71±0.35%	1.72	

APPENDIX B: CROSS-CALIBRATION

B.1	**Data for Cs-137 Cross-calibration factor**		
	Comecer Activity-B (µCi)	Capintec Activity-B (µCi)	Comecer/Capintec
1	185.53	194	0.96
2	187.48	195	0.96
3	183.58	194	0.95
4	190.98	195	0.98
5	185.53	195	0.95
6	187.48	194	0.97
7	179.67	196	0.92
8	185.48	195	0.95
9	183.58	195	0.94
10	181.62	195	0.93
11	185.53	194	0.96
12	179.67	195	0.92
13	183.58	196	0.94
14	185.53	195	0.95
15	187.48	196	0.96
16	190.48	197	0.97
17	185.53	196	0.95
18	183.58	196	0.94
19	189.44	197	0.96
20	183.58	197	0.93
21	185.53	197	0.94
22	189.44	197	0.96
23	183.58	197	0.93
24	181.62	197	0.92
25	189.44	197	0.96
26	183.58	197	0.93
27	183.58	187	0.98
28	185.53	188	0.99
29	183.58	187	0.98
30	185.53	189	0.98
31	179.67	190	0.95
32	185.53	189	0.98
33	179.67	190	0.95
34	181.62	189	0.96
35	187.48	190	0.99
36	181.62	191	0.95
37	183.48	190	0.97
38	185.53	191	0.97
39	181.62	191	0.95
40	187.48	190	0.99
41	183.58	190	0.97
42	186.19	190	0.98
43	181.62	191	0.95

Continuation of Appendix **B**.1			
44	187.48	191	0.98
45	183.58	192	0.96
46	183.58	191	0.96
47	181.62	191	0.95
48	187.48	192	0.98
49	179.67	191	0.94
50	179.48	192	0.93
51	185.53	192	0.97
52	185.53	191	0.97
53	183.58	192	0.96
54	181.62	191	0.95
55	189.62	192	0.99
56	179.67	191	0.94
57	181.62	191	0.95
58	181.62	191	0.95
59	181.62	192	0.95
60	187.48	191	0.98
61	181.67	190	0.96
62	185.53	190	0.98
63	183.53	190	0.97
64	181.62	191	0.95
65	187.48	191	0.98
66	185.53	190	0.98
67	185.53	191	0.97
68	183.58	190	0.97
69	183.58	191	0.96
70	187.48	191	0.98
71	185.53	191	0.97
72	179.67	192	0.94
73	181.62	191	0.95
74	183.58	190	0.97
75	185.53	190	0.98
Mean	184.32	192	0.958
SD	2.86	2.74	0.0176
Error(%)	1.55	1.42	1.84

B.2a Summary of model for Tc-99m calibration curve

Regression Statistics

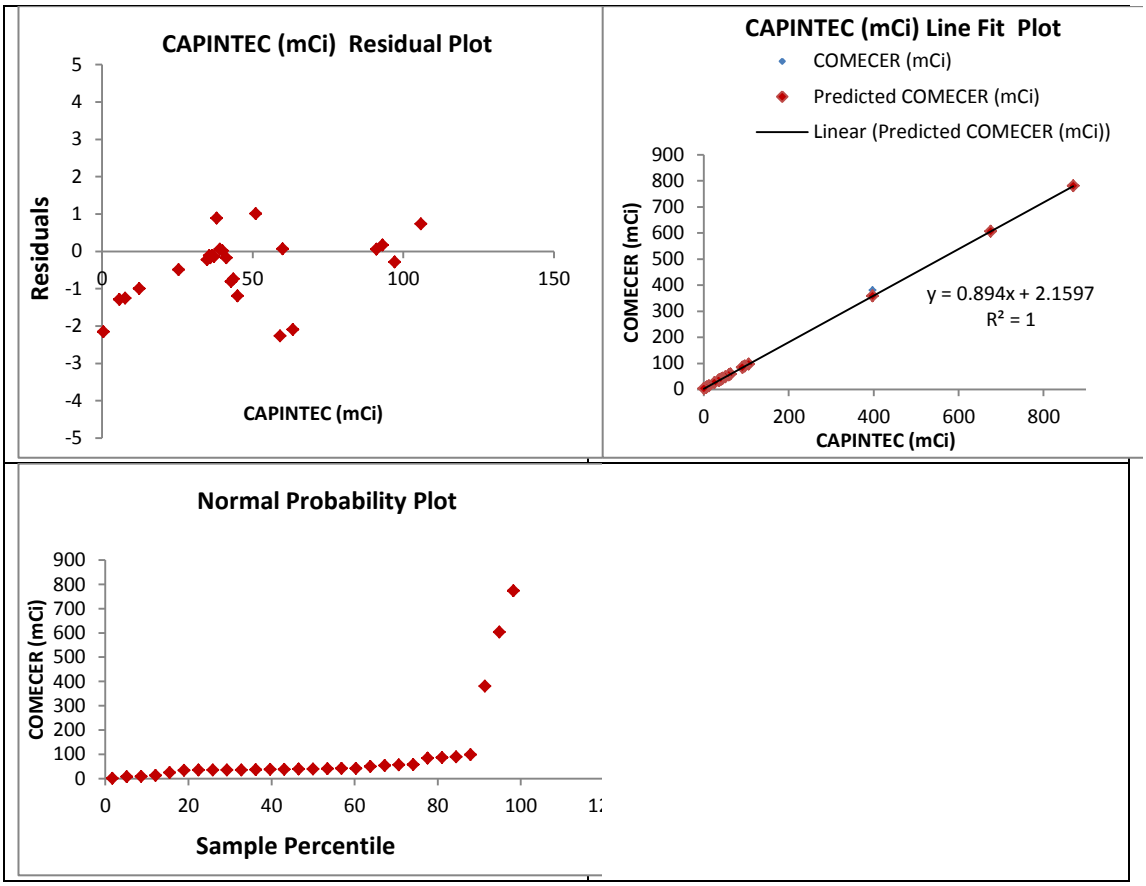
Multiple R	0.99966341
R Square	**0.999326934**
Adjusted RSquare	0.999302006
Standard Error	4.700308121
Observations	29

ANOVA

	df	*SS*	*MS*	*F*	***Significance F***
Regression	1	885658.62	885658.6225	40087.936	2.297E-44
Residual	27	596.5082	22.09289643		
Total	28	886255.13			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	2.159720258	0.9964714	2.167367965	0.039194	0.1151298	4.204311	0.1151298
CAPINTEC (mCi)	0.893993913	0.0044651	200.2197198	2.297E-44	0.8848324	0.903155	0.8848324

B.2b RESIDUALS



APPEENDIX C:

RECOMMENDED FREQUENCY FOR DOSE CALIBRATOR QCS

Criteria for performance checks of dose calibrators

Test	Frequency of testing				Pass/fail criterion
	Upon acceptance/ after repair	At the start of each day of use	Monthly	Annually	
High voltage	✓	✓	✓	✓	±1%
Display	✓	✓	✓	✓	—
Zero adjustment	✓	✓	✓	✓	Within range of adjustment
Clock accuracy	✓	✓	✓	✓	±1 min
Background	✓	✓	✓	✓	±20% of current mean
Check source response (constancy)	✓	✓	✓	✓	±2% of reference value
Accuracy (over normal operating range)	✓			✓	Nuclide dependent; ±2% (SSRLs), ±5% (other laboratories)
Precision	✓		✓	✓	±1%
Relative responses	✓	✓	✓	✓	±2% of reference value
Subsidiary calibrations	✓			✓	±1% of reference value
Linearity	✓			✓	Within 2% (SSRLs) or 5% (other laboratories) of true value over operating range (compare with linear fit of data)
Geometry	✓				New factor must be determined for every change in geometry (SSRLs), or when effect of geometry is >5% (other laboratories)

IAEA TRS 454 (2006)

APPENDIX D:

Cs-137 STANDARD RADIONUCLIDE SOURCE CERTIFICATE

AEA TECHNOLOGY QSA

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28 October 2005

CE

CERTIFICATE

No. 93677 – NK 581

for a Sealed Radioactive Source

Source Type: Dose Calibrator Reference Source

Product code	CDR562
Drawing	VZ-505/1
Source no.	NK 581
Nuclide	Caesium-137

Measurement Data

Activity	9.21 MBq
Overall uncertainty*	3 %
Reference date	13 October 2005
Traceability*	Defined on page 2
Radioactive impurities	Related to Cs-137 (equal 100 %) the following radioactive impurities were detected: Cs-134 < 0.10 %

Leakage and Contamination Test/s

Test method/s*	I
Test/s passed on	18 October 2005

Additional Information

ISO classification*	C.22222

* see page 2 for explanation

AEA Technology QSA GmbH

(Production Manager)

$T_{1/2} = 30.17\,y$