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Sudan University of Science and Technology
College of Graduate Studies

Evaluation of Radiation Exposure for the Employees and Patients at Nuclear Medicine Departments

تقويم التعرض الاشعاعي للعاملين والمرضى للأشعة في أقسام الطب النووي

`A Thesis Submitted for Fulfillment of the Requirement of PhD in Medical Physics

By

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قال تعالي:

﴿ شَهِدَ اللَّهُ أَنَّهُ لَا إِلَٰهَ إِلاَّ هُوَ وَالْمَلَائِكَةُ وَأُولُو الْعِلْمِ

قَائِمًا بِالْقِسْطِ ۚ لَا إِلَٰهَ إِلاَّ

هُوَ الْعَزِيزُ الْحَكِيمُ ﴾

سورة آل عمران الآية (١٨)

Dedication

To doses of the cup blank to give me

a drop of love

To those of the fingers to give us a

moment of happiness

To reap the thorns out of my way

for me to pave the way science

To the soul of my father
Of whom breastfed of love and

healing balm my Mother

To the heart as pure whiteness my

family

and to all my friends

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Abstract

Patients and staff are exposed to ionizing radiation during nuclear medicine procedures. Protection against ionization radiation, known as a carcinogenic agent, is crucial to reducing the probability of cancer effects. The main objective of this study is to evaluate occupational and patient exposure in nuclear medicine departments. Data were collected from]Nilain Diagnostic Cneter and National Center for Radiotherapy and Nuclear medicine in Sudan and King Faisal Specialist Hospital and Research Canter (KFSH&RC) in the Kingdom of Saudi Arabia.

Occupational exposures were measured using TLD-100 thermoluminecent dosimeters, formed of LiF:Mg,Ti (TLD-100). TL signal readout was carried out using a calibrated Harshaw 6600 TLD reader. Patients dose were assessed using the administered activity and computer software to assess the dose distribution. The Administrated Activity was about (810±246 MBq) and the effective dose (mSv) was about (7.1±2 mSv).While for bone scan administered activity was about (796.8±58.2 MBq) and the effective dose was about (4.6±0.31 mSv). The mean annual effective dose and range (in mSv) for Hp (10) and Hp (0.07) being 4.6 ± 7.0 (0.1–25.5) and 5.1 ± 7.3 (0.1–25.5), respectively. The results show five of the radiologists (16% of the total) receiving annual effective doses above the annual dose limits. The outcomes of this survey correlate with the outcome of published studies from other international surveys for patient's doses. The receipt by patients of significant doses during PET/CT procedures depends on the clinical indications for procedures as well as the imaging protocol. CT doses of some 73% of the total patient dose have been found, optimisation of CT aquisition parameters being seen to be vital in reducing the dose to its minimal

value. It is crucial to increase awareness of protective measures and to ensure current radiology department practice follows national and international standards. Rigorous investigation of the work circumstances are essential in mitigating against staff over-exposures, careful dose monitoring also being recommended with additional dosimeters (e.g for the eye lens) if needed.

المستخلص

يتعرض المرضى والعاملون للإشعاع المؤين أثناء فحوصات الطب النووي.لذلك تعتبر الحماية من الإشعاع المؤين ، والمعروف بانه عامل مسرطن ، أمرًا بالغ الأهمية لتقليل احتمال حدوث تأثيرات سرطانية. الهدف الرئيسي من هذه الدراسة هو تقويم التعرض المهني والمرضى في أقسام الطب النووي. تم جمع البيانات من مركز النيلين التشخيصي والمركز القومي للعلاج بالاشعة والطب النووي بالسودان ومستشفى الملك فيصل التخصصي ومركز الأبحاث بالمملكة العربية السعودية.

قيس التعرض المهني باستخدام مقاييس جرعات الحرارية الوميضية (TLD-100) والمكونة من عنصري الليثيوم والفلور. تمت قراءة إشارة مقاييس جرعات الحرارية الوميضية باستخدام قارئ من نوع هارشو (Harshaw6600) . تم تقييم جرعة المرضى باستخدام النشاط الاشعاعي وبرنامج حاسوبي لتقييم توزيع الجرعة الاشعاعية.

بلغ متوسط النشاط الاشعاعي لفحص القلب حوالي 810 ± 246 ميغا بيكريل والجرعة الفعالة 7.1 ± 2 ملي سيفرت. بينما كان النشاط الاشعاعي اثناء فحص مسح العظام 796.8 ± 58.2 ميغا بيكريل والجرعة الفعالة حوالي 4.6 ± 0.31 ملي سيفرت. بلغ متوسط الجرعة الفعالة السنوية السطحية للاطباء و يبلغ 4.6 ± 7.0 والمدى من0.1 الى25.5 ملي سيفرت. كما بلغ متوسط الجرعة العميقة 5.1 ± 7.3 والمدى من 0.1 الى 25.5 ملي سيفرت. تشير النتائج الى أن خمسة من أخصائيي الأشعة (16٪ من المجموع الكلي) يتلقون جرعات سنوية فعالة تزيد عن حدود الجرعة السنوية. بينت النتائج أن خمسة من أخصائيي الأشعة (16٪ من المجموع) يتلقون جرعات سنوية فعالة تزيد عن حدود الجرعة السنوية. ترتبط نتائج هذه الدراسة بنتائج الدراسات المنشورة من المسوحات الدولية الأخرى لجرعات المرضى. يعتمد تلقي المرضى لجرعات كبيرة أثناء إجراءات الفحص البوزيترونيوالمقطعي المحوسب على دواعي الفحص بالإضافة إلى بروتوكول التصويرالمستخدم. بينت الدراسة أيضاً أن جرعات التصوير المقطعي تشكل 73 ٪ من إجمالي جرعة المريض . لذلك أمثلة معايير الحصول على التصوير المقطعي المحوسب مهمة لتقليل الجرعة إلى قيمتها الدنيا. من الضروري زيادة الوعي بالتدابير الوقائية والتأكد من أن ممارسات قسم الأشعة الحالية تتبع المعايير الوطنية والدولية للحماية من الاشعاع. يعد التحقيق الدقيق لظروف العمل أمرًا ضروريًا للتخفيف من التعرض المفرط للعاملين ، كما يوصى أيضًا بمراقبة الجرعة بدقة مع مقاييس أضافية للجرعات (على سبيل المثال لعدسة العين) إذا لزم الأمر.

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List of abbreviations

DRL Diagnostic Reference Level

ICRP International Commission of Radiation Protection

ACR American College of Radiology

IAEA International Atomic Energy Agency

AA Administer Activity

SPECT Single Photon Emission Computed Tomography

PET Positron Emission Tomography

Bq Becquerel

Ci Curie

Sv Sievert

ED Effective Dose

Chapter One

Introduction

1.1 Nuclear medicine dosimetry

Radiopharmaceuticals have been used in nuclear medicine for diagnostic and therapeutic studies since its emergence in 1960 (Cherry et al., 2012). New procedures introduced and new radioactive substances are developed continually to diagnose different clinical conditions. The main sources of occupational exposure in nuclear medicine are during preparation and administration of the radiopharmaceuticals to the patients (99mTc/99Mo) (ICRP, 2012; Edam et al., 2019).

There are limited available data regarding patient's doses and related radiation risks in Sudan. Recent survey showed that there are five nuclear medicine (NM) centres equipped with six nuclear medicine imaging equipment including γ- camera and single photon emission computed tomography (SPECT). This implies a high workload compared with the population in Sudan which is approximately 40 million (Mettler et al., 2008). To our knowledge, no national diagnostic reference level (DRL) was adopted in the country. Thus, the scientific community has to establish local dose reference level to evaluate the current practice leading to dose optimization in clinical environment.

1.2 Fluoro-D-glucose (18F-FDG) PET/CT and patient effective dose

Positron Emission Tomography and associated Computed Tomography (PET/CT) play a powerful role in the diagnosis of several clinical conditions, providing appreciable sensitivity (77%–92%) and specificity (89%–100%) (Zerizer et al., 2010), diagnostic accuracy being improved in the co-registration of 3D anatomical and functional findings in a single image (Huang et al., 2009). Hybrid imaging technology (PET/CT) has been in constant development

since its introduction in 2001, with improved hardware and software technology in detection of primary and metastatic malignancy, further aided by continuous development in radiopharmaceuticals. In addition, PET/CT proves itself to be cost effective, enabled through accurate diagnosis and follow-up, helping to avoid further radiological examinations or invasive examinations. It has been reported that use of PET/CT has improved management of cancer patients in 24% of cases and has provided useful findings for 75% of patients (Townsend, 2008; Wegner et al., 2005; Doshi et al., 2001). In addition to interpretation of both morphological and functional findings, hybrid PET/CT systems also help in cancer staging and image-guided therapy monitoring of treatment for complex pathological conditions (Rohren et al., 2004; Kumar et al., 2012; Dalianis et al., 2006). For assessments using 18F-FDG PET/CT it has been estimated that up to 90% of clinical indications relate to tumour diagnosis, staging and therapy, although applications concerning non-cancerous indications (eg infections and inflammatory disorders) are growing (Zhuang and Codreanu, 2015; Glaudemans et al., 2013).

The undoubted benefits apart, PET/CT patients receive high-energy internal irradiation exposures from 18F-FDG (630 keV positrons (97%), 165 keV electron capture (3%), 511 keV gamma-rays), together with external exposure from heterogenous x-irradiation from CT imaging (with tube voltages ranging between 70 and -140 kVp). Therefore, radiation protection and safety assessment is required in seeking to ensure that patients receive minimal radiation effective dose for maximum imaging benefit. Elsewhere, it has been shown for PET/CT procedures that wide variations in effective doses have occurred, by up to a factor of 10, ranging between 8.0 and 80.0 mSv, when 370 MBq of 18F – FDG was administered (Huang et al., 2009).

1.3. Staff radiation dose and estimated risk in an interventional radiology department

Exposure to ionising radiation can increase the long-term risk of carcinogenesis as well as other effects (ICRP, 2007). Present work concerns radiology department medical staff and the potential for occupational exposures resulting from radiation scattered from the patient. Such levels depend on the type of the radiographic examination and the utilization of protective shields. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) have determined that globally some several million personnel are occupationally exposed to ionising radiation as a result of various applications. Of these, some 10% are medical workers, monitored exposure levels being typically below the defined annual effective dose limit (20 mSv) (UNSCEAR, 2008). Dose limits are set to prevent tissue reaction effects and to decrease the chance of radiogenic cancer incidence. Classified radiation workers (providing for work in controlled areas) are those who may receive annual effective and equivalent doses greater than 6.0 mSv and 150 mSv for the whole body and extremities, respectively. According to the classical dose response model (the linear no-threshold (LNT) model), in stochastic terms no level of radiation dose above background is considered free of the risk of harm (Dahal and Budoff, 2019; Calabrese, 2013; ICRP, 2007). Radiation workers are also at risk of noncancer effects induced by ionising radiation exposure, cardiovascular disease and cataracts included (ICRP, 2007). In interventional radiology (IR) departments, one previous study showed annual effective doses ranging from 7.0 to 49, 4.0 to 6.0 and 0.2–3.0 mSv, for physicians, nurses, and radiographers, respectively (Chida et al., 2013). Physiciansare typically exposed to greater effective dose compared to nurses and technologist, a result of their particular proximity to patients during intervention, receiving a significant fraction of radiation scattered from the patient. In yet another study, regarding nuclear medicine (NM) procedures, staff have been reported to have received on average an annual exposure of 4.5 mSv and 120.0 mSv for whole body (Hp (10) and skin Hp

(0.07) respectively (Alnaaimi et al., 2017), below the dose limits. Clearly, in both departments, staff doses depend on the workload and radiation protection measures (Adliene et al., 2020; Alkhorayef et al., 2020; Wilson-Stewart et al., 2018). Adliene et al. (2020) have reported on surveyed NM departments over the last 26 years, being yet to find a single case of occupational exposure exceeding the annual dose limit. Complacency is not to be envisaged; Bratschitsch et al. (2019) reported that orthopaedists during fluoroscopy and interventions are at greater risk compared to other staff, with six times greater risk of thyroid cancer for females compared to male counterparts.

Thus to prevent avoidable occupational exposure proper methods of protection of personnel are necessary, including use of leaded shields, well-designed department infrastructure, and the practice of safe working procedures. As a key component of this, staff dose monitoring is recommended, in good part ensuring safe working environments, in turn helping to improve good radiation safety practice, also ensuring accord with dose limits. It is apparent that limited studies are available regarding occupational exposure in Saudi Arabia. Accordingly, present study seeks to evaluate staff radiation exposures in such a radiology department, one undertaking interventional investigations.

1.4. Occupational and ambient radiation exposures from Lu-177 DOTATATE during targeted therapy

Since its approval in labelled form by the Food and drug Administration in 2018 (FDA, 2018), lutetium-177 (177 *Lu*), an anthropomorphic beta-emitting radionuclide, has been used for targeted radionuclide therapy (TRT) of neuroendocrine tumours (NETs) and gastroenteropancreatic tumours (GEP). Arising from β^- emission, E_{max} 0.497 MeV, $Range_{max}$ 2 mm; E_{ave} 0.149 MeV, $Range_{ave}$ 0.5 mm (Cremonesi et al., 2006; Pillai et al., 2003), 177 *Lu* emits two γ energies, 0.113 MeV (6.4%), 0.208 MeV (11%). 177-*Lu*, T1/2 6.7 days. It is effectively eradicated from the recipient within two weeks, a result of both the physical and

biological half life (Levart et al., 2019). These characteristics make 177-*Lu* a good choice of radionuclide for theranostic applications, Funkhouser (2002) using the term theranostics in reference to the use of a single radionuclide for both diagnostic imaging and therapy, including for neuroendocrine tumours (Kelkar and Reineke, 2011). The introduction of theranostic agents has helped to provide accurate evaluation of the biodistribution of particular radiopharmaceutials, enabling clinicians to image and monitor dose delivery to the entire organ from the use of a single agent. It also allows evaluation of response prior to subsequent additional dose delivery (Wang and Moore, 2012; Zou et al., 2009), also being noted to improve survival of cancer by up to 17 years from initial diagnosis as well as quality of life (Horsch et al., 2013). Currently, theranostics are widely used for the imaging and treatment of neuroendocrine tumours, the latter known as targeted radionuclide therapy or peptide receptor radionuclide therapy (PRRT). The emission of beta radiation from the 177 *Lu* creates free radicals which induce cellular damage in the cells. The therapeutic effect is mainly caused by the β component (Rmax 2.0 mm), while the emitted γ photons, are generally used for determination of the biodistribution, also being the main source of occupational exposure, also to other patients, as well as to members of the public and relatives. In addition, radiation hazards arise from patient biological expressions, a matter requiring special consideration (Zaknun et al., 2013). 177 *Lu* with Dotatate (DOTA-Tyr3-octreotate (an amino-acid peptide)) or DOTATOC (DOTA-Tyr3-octreotide) has enabled acquisition of up to five single photon emission computed tomography (SPECT) image sets over a period of up to one week following dose administration (Kam et al., 2012). 177Lu-DOTATATE (Lutathera) is also of increasing interest since it shows higher uptake of radioactivity in tumours, lower whole-body retention and better residence times (Bandara et al., 2018). Additionally, 177Lu-DOTATATE presents excellent outcome for thyroid cancer patients, providing an alternative therapeutic option for those with low response to 131I

(Olivan-Sasot et al., 2017). A remaining major concern is specific and nonspecific radionuclide accumulation in the kidneys, with considerable variation having been found in maximal kidney uptake and biological washout. In this regard, Bodei et al. (2008) reported the need for renal-protective agents to reduce the toxicity. In specific regard to present protection interests, while acknowledging that PRRT offers a convincing alternative in the treatment scenario of neuroendocrine tumours (Kolasinska- Cwik ła et al., 2018), recent studies involving outpatient treatment and the protocol have shown staff and comforters to be exposed to a wide range of radiation doses (Demir et al., 2016; Calais and Turner, 2014; Bakker et al., 2006), the potential existing for significant risk. The mean, standard deviation, and range of comforters effective dose was 202.0 ± 43.0 μSv (120.0–265.0 μSv). Personnel effective dose per procedure for pharmacists, nurses and physicists ranged between 2 μSv and 6 μSv. Annual occupational and finger doses ranged between 500- and 1500 μSv. Further of note in regard to the radiation safety from the theranostic use of 177-*Lu* is that this study is believed to be the first of its kind to be conducted in Saudi Arabia. Indeed, even elsewhere dosimetric data for the theranostic use of Lu-177 remains limited (Levart et al., 2019; Kolasinska- Cwik ła et al., 2018; Olmstead et al., 2015).

1.5. Occupational Exposure and radiobiological risk from thyroid treatment with radioiodine -131

Thyroid cancer (TC) incidence is 11% of total cancer in Saudi Arabia, with slightly higher incidence (2^{nd} cancer (12.0%) in females (77.7%) and (8^{th} cancer (4.2%)) in males (22.3%) (SCR, 2018). TC categorized within Saudi females and eighth among Saudi males. This incidence is significantly higher compared to the USA, where thyroid cancer represents only 2.9% of all malignancies and 4.6% of all female malignancies (Hussain et al., 2013). The highest incidence was in females (female to male ratio at 3.48:1). Median age and range at diagnosis was 39.0 (4.0–95.0) and 44.0 (8.0–95.0) years for females and males, respectively

(SCR, 2018). Incidence of thyroid cancer continues to increase in Saudi Arabia with a 24% increase in males and a 63% increase among females over the ten year period. It was estimated that about 60% underwent combined modality treatment consisting of surgery, radiation and hormonal therapy for TC. Thyroid disease treated with radioiodine include cancer and non-cancerous diseases such as hyperthyroidism (thyrotoxicosis). Both disease treated with radio-iodine therapy I-131 to detect and treats any areas of residual thyroid tissue or tumor or decrease the thyroid activity to attain the standard hormonal level. Radioactive iodine-131 (Z=53, $T_{1/2}$=8.02 days,) is used as unsealed source in theranostic clinical applications for therapy and diagnosis of thyroid disorders for last seven decades because it decays by 90% by beta emission (606 keV) and 10% by gamma emission (364 keV) (Bozkurt & Özcan, 2018). The advantage of cancer treatment using ^{131}I ablation with activity ranged between 1110 MBq to 7400 MBq (30–200 mCi) , total thyroidectomy over thyroid provide excellent option by allowing healthy tissues and cells provide the necessary hormones and monitoring the disease using thyreoglobulin serum level (Calegaro J& Teixeira, 2007; Schlumberger et al., 2004). In addition to that, radioactive iodine (RAI) therapy improves the survival rate of patients with cure rates in excess of 90%. Exposure to ionising radiation from different sources (fallout, Chernobyl accident, medical exposure, etc) is one of documented causes of cancer worldwide due to its high energy which lead to DNA damage (ICRP 2018). Medical perssonel (Medical physicist, Technologist, Physicians and nursing staff) interact with patients after administration of radioiodine and during hospitalization; hence they exposed to ionizing radiation emerging from the radioactive patients. Radiation exposure depends on the time, distance and shielding and workload, thus staff exposure is variable. Recent studies showed that medical physicists, technologists and nurses were 604, 680 and 1000 µSv respectively (Alkhorayef et al., 2018; Bitar et al., 2013). Unsealed radiopharmaceuticals such as ^{131}I, which is frequently used in nuclear medicine

department for therpeutic purposes, may cause significant occupational dose up to 7.7 mSv per year (Bitar et al., 2013). Thus, It is essential to ensure that staff recieved the minimal occupational dose limit from external and internal contamination due to inhallation of radioactive iodine due to its volatile compound (airborne iodine as anaerosol, CH_3I and and iodine vapor ($I_{2)}$) (30% of radioactive iodince concentrated in theyroid) (Ramos et al., 2013; IAEA,1999; Thrall and Ziessman, 1995). Miszczyk et al., reported staff contamination with radioiodine at nuclear medicine depatrtment up to 217 ± 56 Bq. Therefore, measurement of occupational radiation exposure due to external and internal exposure and assessment of its biological risk is crucial to ensure that the staff working in safe environment.

1.4 Problem of the Study:

Patients are exposed to ionizing radiation resulting from radioisotopes administration. The patients' doses in nuclear medicine procedures ranged between 740 -1110 MBq for bone scan, 296 – 1110 MBq for cardiac scan, 111 – 740 MBq for renal scan, and 74 – 370 MBq for thyroid scan (Shackett et al., 2009). The radiation risks resulting from radiopharmaceuticals administration must be balanced against the projected benefit from the examination to prevent patients from avoidable detriment (ICRP 106, 2007). On the other hand, the radiation exposure from the patient to the member of staff and public including patient's family members, especially radiosensitive groups such as children, is of great concern and the related risk needs precise evaluation. Nowadays, many gamma emitter radioisotopes are used in diagnostic investigations, for instance 99mTc,111In, 123I, 131I, 201Tl,18F, etc. (Lassman el al., 2004). To improve radiation dose optimisation in nuclear medicine, the International Commission on Radiological Protection (ICRP) recommendation (ICRP 73, 1990), the International Atomic Energy Agency (IAEA), and the European Commission (EC, 1997) recommended the use of administrated activity and effective dose as radiation quantities for evaluating patients' doses nuclear medicine investigation and reporting diagnostic reference

level. Although, the radiation risks associated with nuclear medicine exposure is below the documented radiation risks (100 mSv), practitioners are encouraged to reduce the dose to its minimal value because radiation induced cancer risk has no threshold.

The associated CT contribution to patient total effective dose were reported to range between 54% and 80%, depending on the imaging protocol and type of procedure; the maximum radiation risk for 20 years olds was estimated to be 1 cancer case per 200 procedures (Huang et al., 2009). While the frequency of PET/CT procedures is increasing, limited data are available regarding patient exposures and related risk. Thus, there is a need for detailed patient exposure assessment based on the type of procedure (Tulik et al., 2017; Chen, 2014; Vanhavere et al., 2012). Previous studies have tended to focus on patient effective doses resulting from a range of radionuclide administrations, for different clinical indications and different types of procedure (Tulik et al., 2017; Chen, 2014; Huang et al., 2009). It is thus critical to provide patient effective doses based on both clinical indications and procedure type, seeking to provide reasonable data suitable for effective dose optimisation planning and to establish diagnostic reference levels (DRLs). In addition, due to the relatively high radiation effective doses resulting from PET/CT procedures, it is important to demonstrate that the benefit of the PET/CT scan far outweighs the projected cancer risk from ionising radiation exposure.

1.5 Objectives of the Study:

1.5.1 General Objective

The main objective of this study is to assess the impact of imaging protocol on occupational and patient exposure in certain nuclear medicine procedure.

1.5.2Specific objectives

1. To evaluation of imaging protocol in cardiac, renal and bone scan.

2. To calculate dose distribution to patient and staff dose and ambient dose.
3. To estimate the specific organ equivalent dose.
4. To evaluate patients and occupational exposure during therapeutic radioiodine and measure the ambient doses and estimate the radiation risk.

1.6 Thesis overview:

This thesis has been classified into five chapters, based on the college of graduate studies requirements. Chapter one Introduction provides the necessary information about the problem of study and thesis objectives: chapter two, concerns with the theoretical background of nuclear medicine, instrumentation imaging techniques, and protocols. The materials and methods are presented in chapter three. Chapter four of the study results, and chapter five concerns the study's discussion, conclusions, and recommendations.

Chapter Two
Theoretical Background

2.1 Molecular Imaging

The principle of radiotracer was first introduced by the Hungarian chemist George de Hevesy in the 1920s (Gray et al., 1991). This technique was widely used for in vivo imaging in vivo in vitro procedures. The introduction of this technique lead to the emergence of nuclear medicine imaging, which a noninvasive technique of choice of evaluation physiological disorders and molecular imaging (Gray et al., 1991)

2.1.1 De Hevesy: experiment:

In 1935 the main issue that George de Hevesy interest about when he came to Niels Bohr's institute in Copenhagen was to find radionuclide which could be used in biological research. He chose ^{32}P and began a series of experiment where different phosphorus compounds were given to animals in order to study metabolism and distribution of the substances. He published the first results in the journal 'Nature' in September 1935 with Danish physician O. Chievitz. George de Hevesy et al that the result of the published that new information about the metabolism of the skeleton, and the result strongly support the view the bone formation is a dynamic process, the phosphorus atoms are taking up continuously by the bones which are partly or wholly lost again and are replaced by other phosphorus atoms (Chiewitz & de Hevesy, 1935)

In 1943 the Nobel Prize in chemistry was awarded to De Hevesy and he moved in the same year to Sweden where he continued his research at Stockholm University, and he focused primarily on studying the transformation of nucleic acids using ^{32}P as a tracer, until his death in 1966 at the age of 81 years. The European Association of Nuclear Medicine report that the

De Hevesy as the father of radioactive tracer method and hence the father of nuclear medicine. (Chiewitz & de Hevesy, 1935)

In 1930 E. Lawrence at the University of California developed the first cyclotron and at the end of 1933 he had assembled a machine capable of yielding a beam of 3 MeV deuterons and with power equal to massive amounts of radium in a Ra-Be source. In 1942, E Fermi and co-workers realized the first self-sustained nuclear chain reaction and started the construction of the nuclear reactor. The reactor produces millions of times radioactive isotopes than that produced by the cyclotron. In the June 14, 1946 issued of the journal science published that now the radionuclides for medical and biological research were available. At the end of 1947 began of special importance for the start of nuclear medicine in the Nordic countries was the production of radionuclides at Harwell in the UK and five shipments to UK where made that year, In 1951 this amount increasing to 2800 excluding shipments to the Nordic countries hospitals(Trott, 1979)

The most widely used radionuclide in diagnostic nuclear medicine imaging in 1962 is $^{99}Tc^{m}$, was recommended as valuable agent by P.V. Harper and co-workers at the Argonne National Laboratory in the USA. This radionuclide is a daughter of ^{99}Mo which can be formed by fission or by neutron activation of stable Mo. The separation of $^{99}Tc^{m}$ from ^{99}Mo was initially reached by properly complex chemical methods. (4)

2.2 Rectilinear scanner:

In New York City in 1902 Cassen was born. He studied physics and mathematics at Royal collage of science in London, from which he graduated in 1927. He gained his doctorate from California Institute of Technology (CIT) in 1930. From 1930 to 1932 he was a National Research Council Fellow at Princeton University, and from 1934 to 1939 he was a physicist at Harper Hospital in Detroit, MI. after 5 year stint as a research physicist with Westinghouse

Research Laboratory, Philadelphia, PA, Cassen returned to CIT in 1944, where he worked on war-related project. Cassen combined the staff of the University of California Los Angeles (UCLA) Laboratory of Nuclear Medicine and Radiation Biology, which at the time was called the UCLA-U.S. Atomic Energy Commission Project, where he continued working until his death in 1972 (Harper et al., 1961).

By B. Cassen et al at UCLA it used a crystal of calcium tungstate and was specifically planned for localization of radioactive iodine in the thyroid. The instrument initially performed well and its efficiency was additional improved by the overview of large sodium iodide crystals and end windowed photomultiplier tubes. In the following years, a variety of external counting procedures, employing scintillation detectors, were developed fluctuating from pre-operative localization of brain tumors to determination of cardiac output and kidney function (Tapscott et al., 1998).

In 1950 Clinical studies using human subject were performed and Cassen testified his results in an issue of Nucleonic that year. Two of Cassen's colleagues, Cliff Reed, biomedical engineer and Larry Curtis, a technician, assumed commercial production of the rectilinear scanner. The rectilinear scanner rapidly developed the ordinary instrument used in nuclear medicine imaging. Its disadvantage, yet, was that the time required to scan a big organ like the lungs or the skeleton, was sizeable and that dynamic examinations were difficult. Hence the need for a large stationary detector became understandable (Cassen et L., 1950).

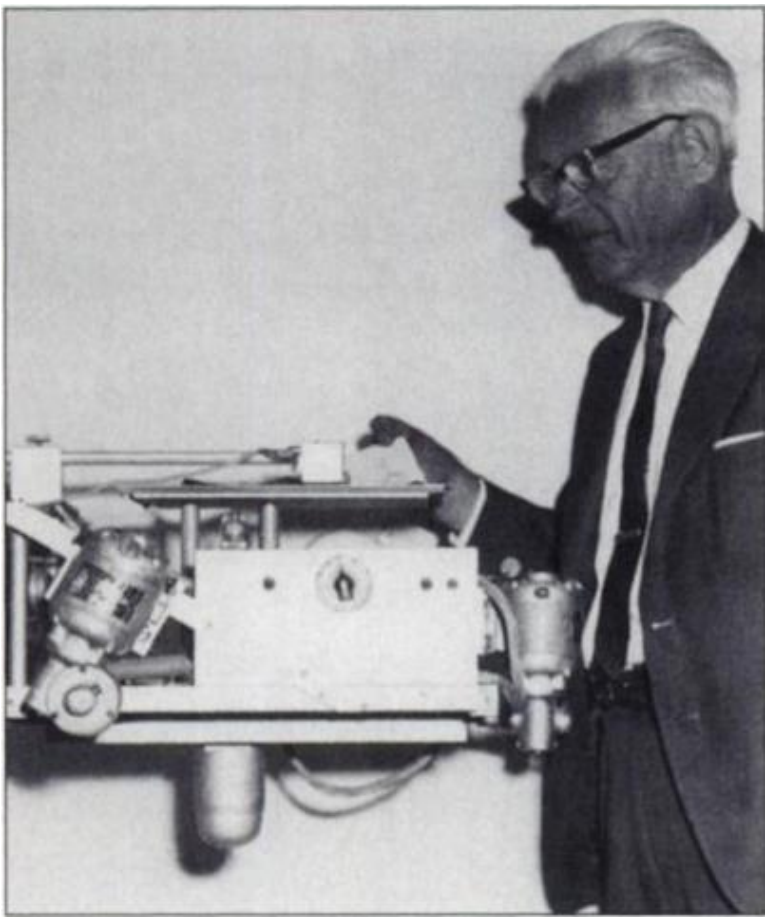

Figure 2.1: the rectilinear scanner

2.3 Gamma Camera (Anger Camera):

Anger was born on May 24, 1920, in Denver, CO. His father was a first-generation German-American and his mother was British –American. Once he was 5 years old, his family moved to Long Beach, CA, where he went into the Long Beach public schools. Viewing an early concern in electronics, he made a television set from scratch whereas at Long Beach Junior College in the 1930- a remarkable achievement at a time when the technology was new. From Long Beach he joined engineering school of the University of California at Berkeley, where he was encouraged by J.V. Lebacqz, who was at work on a seminal text on pulse generation. In 1943 Anger received his bachelor's degree in electrical engineering. Anger was among to improve radar during the Second World War at Harvard's Radio Research Laboratory. In 1948 Anger went to work at the Donner Laboratory, part of the larger Berkeley Laboratory

that had been founded by the Nobel laureate Ernest O. Lawrence in 1931. John H. Lawrence, Ernest's brother, was head of the Donner Laboratory, and, like his staff members, was devoted to finding new ways to apply radioisotopes in medical diagnostic and treatment. Anger's direct supervisor was Cornelius Tobias, one of the many Hungarian immigrants who came to the United States in the pre-war years and who donated so much to growth of the radiation sciences (Jonsson et al., 1957).

Tobias was establishment member of the Donner Laboratory and initiated the study of the biologic effects of cosmic rays. At the lab, he worked with Luis Alvarez and Emilio Segre, who would also become Nobel laureates. Tobias's career at the lab spanned more than 40 years, and among his many activities were the use of ^{11}C in studies of oxygen deficiency in pilots and the use of xenon gas as an anesthetic.

Amongst the first projects Tobias assigned to his new employee was alteration of the 184 inch cyclotron so that it could be used for irradiation of pituitary tumors with high energy deuterons. (Jonsson et al., 1957).

In 1950 the main of Anger's major contributions to biochemistry and nuclear medicine was the creation of a practicable well counter. The devise used anthracene crystal organized around a well-like compartment to evaluate radioactivity in liquids located in small glass vials. Well counters soon became the most broadly used instruments in radiation chemistry.

In 1952 anger was report the first gamma camera available on the use of pinhole camera for in vivo studies of a tumor using ^{131}I . Gamma photons from ^{131}I in a patient with metastatic cancer close the skin were used to produce images on great piece of photographic paper with pinhole collimators in opposite of a thallium-activated sodium iodide crystal that was 5/6 inch thick. The apparatus was improved further, as reported in 1954 ((Jonsson et al., 1957).

In the 1957 Anger was described his first scintillation camera in an article entitled “A new instrument for mapping gamma-ray emitters”. This camera used sodium iodide crystal 4 inches in diameter, optically coupled with 7 photomultiplier tubes. With assistance from Tobias and John Lawrence, the Atomic Energy Commission (AEC) in 1958 released the rights to Anger, who obtained U.S. patent #3011057 on scintillation camera that would be known by his name.

With the new Anger camera in July 1962, he instantly recognized the importance of Anger’s work. In 1963 the 2 researchers defined the localization of brain tumors with the “positron scintillation camera” (J Nucl Med. 1963; 4:326-330). This characterized the first clinical use of the positron scintillation camera and was an extension of the camera with an instrument that Anger had termed in 1958 (Rev Sci Inst. 1958; 29:2733). Gottschalk was the positron-emitting ^{68}Ga, with half-life of 68 minutes. This nuclide was acquired by elution from a germanium-gallium generator system. The new camera had an 11.5 inch diameter sodium iodide crystal, which made it potential to study the entire brain. Anger and Gottschalk studies 25 patients and matched the results with those from the ^{203}Hg-neohydrin rectilinear scanner images (Wagner et al., 2003).

In acknowledgment of his work, Anger established a Guggenheim fellowship in 1965 to spread out his research efforts. After a long fruitful tenure at the Berkeley laboratory, anger retired in 1982. He published further than 90 journal articles, 22 book chapters, and held 14 U.S. patents during his career. His accomplishments have been documented with numerous awards and honors, including the 1991 von Hevesy prize from the Georg von Hevesy foundation, based in Zurich, Switzerland. He was the first person to receive the SNM Education and Research foundation’s Cassen Prize for distinguished achievement in Nuclear Medicine. He continues to live in California, where he follows a lifelong attention in photography.

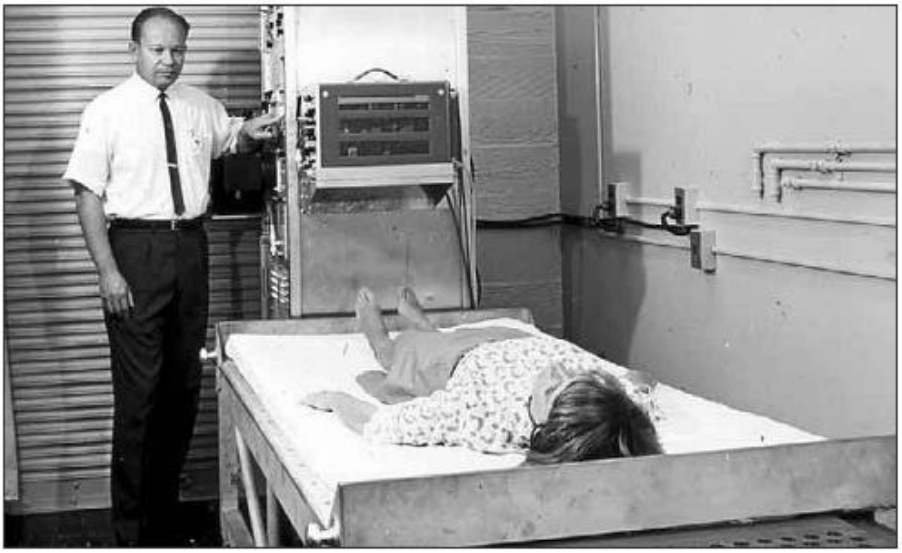

Figure 2.2: Hal Anger in 1965 with the whole-body scintillation scanner at the Donner Laboratory. The small holes in the foreground are part of the collimator. From the collection of Henry N. Wagner, Jr., MD.

Figure 2.3: anger camera

Anger is known internationally for his achievements in imaging technology. This photo was taken at the Deutschen Gesellschaft für Nuklearmedizin in 1966. From the collection of William G. Myers, MD (Wagner et al., 2003).

2.4 Principle of hybrid imaging:

Positron emission tomography (PET) and single photon emission computed tomography (SPECT) system are used image distribution of radiopharmaceuticals in order to afford physicians with physiological information for diagnostic and therapeutic purposes.

But, these images frequently absence required anatomical detail, a fact that has activated the development of a new technology characterized hybrid imaging (Delbeke et al., 2010).

Hybrid imaging is a term that is used to describe the combination of x-ray computed tomography (CT) systems with nuclear medicine imaging devices (PET and SPECT systems) in order to provide the technology for obtaining images of anatomy and function in a registered form at during a single imaging session with the patient positioned on a common imaging table. There are two main benefits to this technology. Main, the x-ray transmission images acquired with CT can be used to perform attenuation correction of the PET and SPECT emission data. In addition, the CT anatomical images can be bonded with the PET and SPECT functional images to deliver accurate anatomical localization of regions of questionable uptake of radiopharmaceuticals. This part will offer a evaluation of SPECT, PET, and CT equipment and then deliberate the technology involved in combining these systems to provide the capabilities for hybrid imaging (Delbeke et al., 2010).

2.4.1 Single Photon Emission Computed Tomography (SPECT):

Nuclear medicine techniques have been implemented using a scintillation camera for many years. Initially, multiple planar projections were acquired to arrange for diagnostic information, but, in recent times, the techniques of SPECT have been used. During this time, the scintillation camera has advanced to a high-quality imaging device, and much of this progression is due to the combination of digital technology into every feature of the data acquisition, processing, and display processes.

Conventional planar images generally suffered from poor contrast due to the occurrence of overlying and underlying activity that interferes with imaging of the region of interest. This is produced by the superposition of depth information into single data points collected from perpendicular or angled lines of travel of photons from the distribution being studied into the holes of the parallel hole collimator fitted to the scintillation camera. The resulting planar image is low in contrast due to the effect of the superposition of depth information (Delbeke et al., 2010).

2.4.2 Positron Emission Tomography (PET):

Previous discussions have been associated to the imaging of single photon emitting radionuclides using conventional scintillation camera systems. Another classification of radionuclides that have applications in nuclear medicine is positron emitters that can be imaged using specially designed PET systems optimized for the exclusive decay properties of these radionuclides. Nevertheless, these approaches suffered from absences in the efficiency of NaI(Tl). Robertson and coworkers14 and Brownell and Burnham15, 16 established special purpose positron imaging systems in the early 1970s, but the modern day PET scanner began to progress in 197517 with the work of Phelps and his associates manufacturing a system of detectors operating in coincidence mode and surrounding the patient to deliver transverse section imaging competences.18–22 Positron emitting radionuclides are distinguished by the unique method by which they are detected. The positron is a positively charged electron. When positron emitted from a radioactive nucleus, it will losing all of its energy and coming to rest in a very short distance. The negatively charged electron immediately combined with the positron, and the result of collision of two particle (electron and positron) are completely converted into energy in the form of two 511 keV photons. This process is termed annihilation. The two annihilation photons leave the site of their production at 1808 from each other. This procedure can be detected as shown in Fig. 2.4 by using small, dual opposed

detectors connected by a timing circuit, termed a coincidence circuit, to simultaneously detect the presence of the two annihilation photons, a signature of the positron decay process.

The timing window must be small, 7–15 ns, in order to decrease the opportunity of detecting photons from two separate decay processes, i.e., random events. The spatial resolution of the imaging system is primarily determined by the size of the detectors, combined with the uncertainty due to the travel of the positron before annihilation which is typically less than 0.5 mm in tissue. In clinical imaging systems, many small detectors are used in multiple rings to provide high sensitivity for detection in the region being examined as shown in Fig. 2.5. [9]

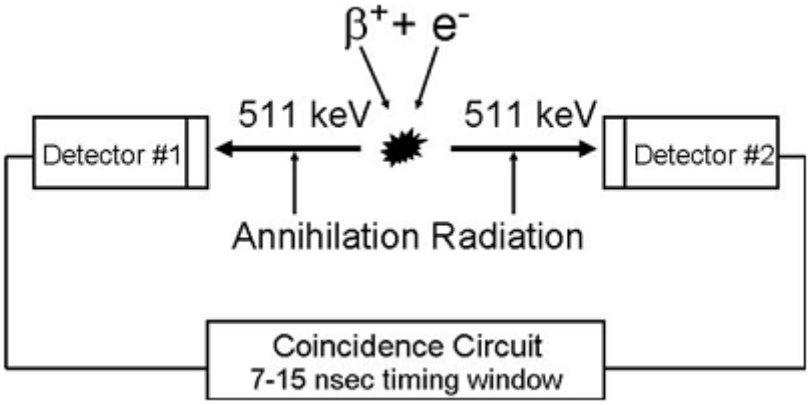

Figure 2.4: Block diagram of a two-detector grouping with a coincidence timing window

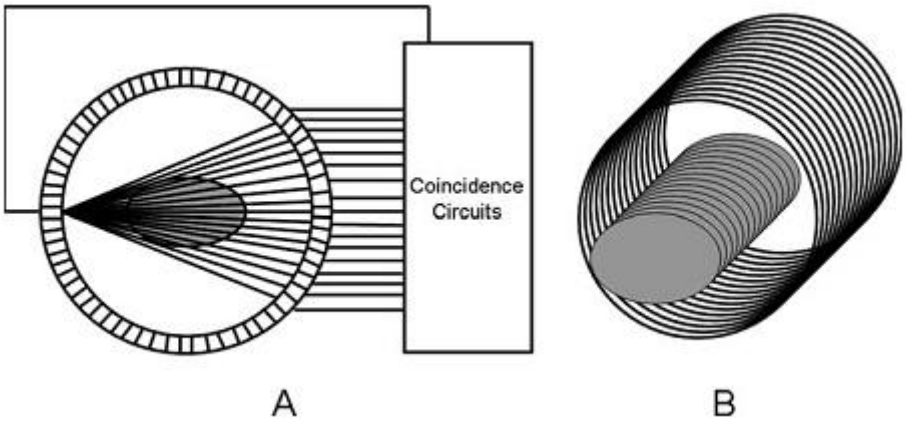

Figure. 2.5 One ring of detectors from a multi-ring PET system.

2.5 Clinical SPECT/CT Systems

Clinical SPECT/CT systems presently available from manufacturers typically have dual-head scintillation cameras located in front of the CT scanner and sharing a common imaging table. There are two approaches to clinical SPECT/CT applications. Firstly the use of a low-output, slow-acquisition CT scanner, the Hawkeye1 with dual-head InfiniaTM manufactured by General Electric Healthcare Systems. The CT scanner involves of a low-output x-ray tube (2.5 mA) and four linear arrays of detectors and can obtain four 5-mm anatomical slices in 13.6 s through a high contrast spatial resolution > 3l p/cm. The obtained images with the system are not sufficient quality to be used for diagnostic but are sufficient to be used for attenuation correction and anatomy correction with the emission scan. The slow scan speed is truly a benefit in regions where there is physiological motion since the CT image blurring from the motion is comparable to that of the emission scans resulting in a good match in fused images. Radiation dose from this system is typically < 5 mGy (500 mrads) compared to values of 10–100 mGy (1–10 mrads) for applications using radioisotope transmission sources. [9]

2.6 Clinical PET/CT Systems

Clinical PET/CT systems are only available with diagnostic CT scanners, and systems are normally acquired with 4, 8, 16, or 64 slice capability providing images of sufficient diagnostic quality. As with SPECT/CT systems, the CT scanners can be functioned at reduced tube current if the scans are only to be used for attenuation correction. [9]

The precise registration of a SPECT or PET scan with a CT scan depends on careful calibrations of the sequential data acquisition processes and assumes that there is no patient movement through the acquisitions. However, the natural physiological motion of the lungs and heart poses possible difficulties. These difficulties happen due to the fact that CT

acquisitions are fast, i.e., images of multiple slices are acquired in less than a second, and SPECT and PET acquisitions are slow, i.e., several minutes per view. The relatively fast motion of the heart results in the motion being smoothed out in both data sets so that a reasonable registration is usually obtained. However, the slower motion of the lungs often results in a mis-registration at the base of the lungs that can be source of trouble in the accurate localization of lesions in this area. The new PET/CT systems are available with respiratory gating capability so that both the CT and the PET scan of the chest can accurately be registered by removing the effects of lung motion. [9]

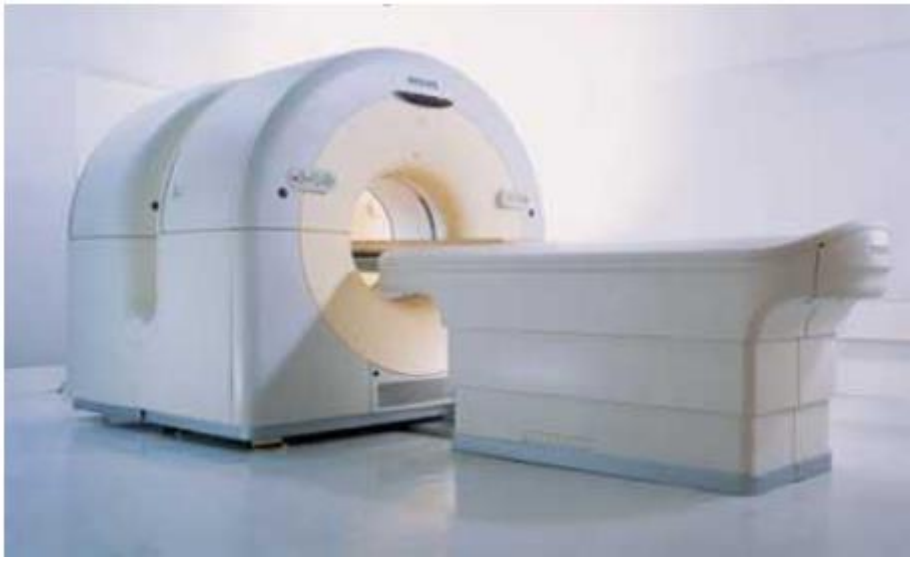

Figure 2-6 Images of CT PET scanner

2.7 PET/MRI system:

The concept to add PET and MRI (Figure2 -7) grow as early as the mid-1990s, even before PET/CT was inserted. The PET/MRI combination needs 3 risky technologic steps that adjust state-of-the-art PET and MRI. Main, the photomultiplier technology must be replaced with magnetic field–insensitive photodiodes. Additional, compact PET detectors must be built so that it shouldn't interfere with the field gradients or MR Radiofrequency. Lastly, the MRI scanner must be modified to accommodate the PET detectors and to permit simultaneous data acquisition without alternate interference. It is sensible to imagine that brain PET/MRI will

offer new insights in the field of neuroscience and neurologic disorders, such as neuro degeneration, brain ischemia, neuro-oncology, or seizures ((Delbeke et al., 2010) it is workable with current prototypes and future-generation systems to simultaneously study brain function, metabolism, oxygen consumption, and perfusion. The precise spatial and temporal recording of data will permit the attribution of functional and molecular info to even anatomically small brain structures. Firstly, it may become possible to study the association of local radiotracer uptake and brain perfusion. Time-dependent procedures such as perfusion variations in stroke patients may depend on simultaneous diffusion-weighted imaging and detection of PET perfusion to define the optimal therapy procedure. In neuro-oncology, an exact spatial match between PET and MRI data is compulsory for both radiation therapy planning and biopsy guidance. PET might detect particularly small lesions with higher sensitivity than MRI Lauenstein.

Figure 2-7 Images of MRI PET scanner

2.8 Dosimetry in Nuclear Medicine

In Nuclear Medicine, radiotracers can be administered intravenously (mostly), orally or by inhalation but, either way, different amounts of activity will be

deposited, and accumulated, in different organs and tissues (and not exclusively in the target organ). If we were to consider a homogeneous mass of tissue, where a radionuclide is uniformly distributed, the dose rate to that same tissue would depends on three factors:

1. The concentration of the nuclide in the tissue (in Bq/kg);

2. The average energy released per disintegration (in MeV);

3. The fraction (let us call it ϕ) of that released energy that is actually absorbed in the tissue.

The MIRD (Medical International Radiation Dose) Committee has developed a simple approach to compute the absorbed dose in specific organs, in which ϕ, divided by the estimated mass of the organ, is considered to have a specific value for each radionuclide, source organ (where the nuclide is accumulated) and target organ (for which the absorbed dose is to be determined). This value is often referred to as S - the mean absorbed dose per unit cumulative activity, available in standard tables. The absorbed dose in the target organ may be computed as expressed in Equation 2.1: (Stabin 2006, MIRD 2018).

$$D = \tilde{A} \cdot S \qquad \rightarrow \textbf{(2.1)}$$

where $\tilde{A}$ is the accumulated activity in the source organ, obtained from biokinetic data (standard biokinetic models are now being developed by the ICRP, to assess activity "flow"

through the complex physiological compartments existing within the human body). Ultimately, the total dose to a particular target organ would have to include the contributions of all the identified source organs (MIRD 2018).

Although undoubtedly relevant, these complex calculations are impracticable to perform in a daily basis, whenever the administration of radionuclides to a patient is concerned. Usually, the absorbed dose or the effective dose for the patient are never estimated – the administered activity is the one parameter taken into consideration when implementing the second and third principles of Radiation Protection (optimization and dose limitation). For instance, the activity to be administered is mostly calculated, in adults considering patient's weight and, in some cases, predefined suggested dosages and standard maximum levels of activity, per examination. For pediatric patients, the EANM (European Association of Nuclear Medicine) has published a Dosage Card on which the child's body weight is also the determining factor, but subject to a minimum acceptable amount of activity.

Finally, in Nuclear Medicine imaging, the radiation dose for individuals near the injected patient is also something to considerer, since the patient becomes a radiation source from the moment he is administered the radiotracer. For instance, a Nuclear Medicine technologist performing a PET study usually is exposed to a considerably higher dose, when compared that he/she would be exposed in a conventional Nuclear Medicine examination. Dose to the extremities may also be considerable when radioactive materials are handled, namely associated to the syringe manipulation at the different phases of the medical procedure (MIRD 2018).

2.8. Estimates of Effective Dose in Nuclear Medicine Imaging Procedures

According to a special report published in Radiology, in 2008 {54} Nuclear Medicine effective doses for the patient can vary between 0.3 and 20 mSv:

Nuclear Medicine Examination	Effective Dose (mSv)	Administered Activity (MBq)
Brain (^{99m}Tc-HMPAO)	6.9	740
Thyroid scan (sodium ^{123}I)	1.9	25
Cardiac stress-rest test (^{201}Tl chloride)	40.7	185
Renal (^{99m}Tc-MAG3)	2.6	370
Bone (^{99m}TC-MDP)	6.3	1110
Tumor (^{18}F-FDG)	14.1	740

Table 2.2 – Adult effective doses from some Nuclear Medicine examinations. {54}

It is also important to refer the estimates of effective doses for Nuclear Medicine technicians and individual members of the public in close proximity to a "radioactive" patient.

2.8 RADAR

In the begging of this century, an electronic resource was established on the internet to provide quick, worldwide dissemination of important dose quantities and data. The RAdiation Dose Assessment Resource (RADAR) established a web site at www.doseinfo-radar.com and provided a number of publications on the data and methods used in the system. The RADAR system uses dose calculation formula as (Stabin 2006)

$$D = N * DF \qquad (2.2)$$

where N is the number of disintegrations (integral of a time activity curve for a source region) that occur in a source organ, and DF mathematically equal to S factor as defined in the MIRD system. RADAR members produced compendia of decay data, dose conversion factors and catalogued standardized dose models for radiation workers and NM patients, among other

resources. They also produced the widely used OLINDA/EXM personal computer software code, which used the equations shown here and the input data from the RADAR site (Stabin 2006).

2.9. International Commission on Radiological Protection (ICRP)

The ICRP has developed two comprehensive internal dosimetry systems intended to use in occupational settings (mainly the nuclear fuel cycle). The real innovation in the ICRP 30 system is the so called effective dose equivalent. Certain organs or organ systems were supposed as a dimensionless weighting factors that are a function of their assumed relative radiosensitivity for expressing fatal cancers or genetic defects. The assumed radiosensitivities were derived from the observed rates of expression of these effects in various populations exposed to radiation. Multiplying an organ's dose equivalent by its assigned weighting factor gives a weighted dose equivalent.

The equivalent dose can by calculated by the equation (2.8) below:

$$H_T = W_R * D_{T,R} \qquad (2.3)$$

$D_{T,R}$ is the mean tissue or organ dose delivered by type R radiation. and W_R is the radiation weighting factor. The sum of weighted dose equivalents for a given exposure to radiation is the effective dose equivalent. It is the dose equivalent that, if received uniformly by the whole body, would result in the same total risk as that actually incurred by a non uniform irradiation, and can be given the equation (2.4):

$$E = \Sigma\, W_T * H_T \qquad (2.4)$$

where H_T is the equivalent dose in organ or tissue T, and W_T is the tissue weighting factor. Effective dose is totally different from the dose equivalent to the whole body that is calculated using values of specific effective energy (SEE) for the total body. Whole body doses are often meaningless in internal dosimetry because of non uniform and localized energy deposition is averaged over the mass of the whole body (i.e. 70 kg). One real difference that exists between doses calculated with the ICRP II system and the ICRP 30 (and MIRD) system is that, in the ICRP II they used a very simplistic phantom to estimate their absorbed fractions. All body organs and the whole body were represented as spheres of uniform composition. In addition, organs could only irradiate themselves, not other organs. So, although contributions from all emissions were considered, an organ could only receive a dose if it contained activity, and the absorbed fractions for photons were different from those calculated from the more advanced phantoms used by ICRP 30 and MIRD. However, the major revolution is now underway, involving the use of realistic and patient specific body models based on medical image data (MRI, CT with both PET and SPECT). This permits the calculation of highly detailed 3D dose distributions, dose volume histograms and other data by using Monte Carlo codes. The last revolution that is needed to truly push internal dosimetry into a Golden Age is the linking of such high quality radiation dose estimates to biological effects, which is only now being explored with much efforts (Stabin 2006, ICRP, 2010).

2.10. Previous studies

Ana S.F. Ribeiro et al, 2020 studied the Medical imaging is on average the largest source of artificial radiation exposure worldwide. This study seeks to understand patient's awareness of radiation exposure derived from nuclear medicine diagnostic scans and assess if current information provided by leaflets is adequate.

Methods Single-centre cross-sectional questionnaire study applied to bone scan and FDG PET/computed tomography patients, at a nuclear medicine and PET/computed tomography department over a 15-week period in 2018. Questionnaires on dose comparators were designed in collaboration with patients, public, and experts in radiation exposure. Qualitative data were analysed using thematic analysis and quantitative data using SPSS (V. 24).

Results A total of 102 questionnaires were completed (bone scan = 50; FDG PET/computed tomography = 52). Across both groups, 33/102 (32.4%) patients reported having a reasonable understanding of nuclear medicine and 21/102 (20.6%) reported a reasonable knowledge of ionising radiations. When asked to compare the exposure dose of respective scans with common comparators 8/50 (16%) of bone scan patients and 11/52 (21.2%) FDG PET/computed tomography answered correctly. On leaflet information, 15/85 (17.6%) patients reported the

leaflets do not provide enough information on radiation exposure and of these 10/15 (66.7%) commented the leaflets should incorporate more information on radiation exposure dose.

Conclusion More observational and qualitative studies in collaboration with patients are warranted to evaluate patients' understanding and preferences in communication of radiation exposure from nuclear medicine imaging.

C. Lindholm et al 2020, The eye lens exposure among 16 technicians in two nuclear medicine departments at university hospitals in Finland was investigated by measuring the operational

quantity Hp(3) using EYE-D dosemeters. For all workers, the annual mean Hp(3) was estimated to be 1.1 mSv (max. 3.9 mSv). The relation between Hp(3) to routinely monitored personal dose equivalent Hp(10) was clearly correlated. Considering individual dose measurement periods (2–4 weeks), the Hp(3)/Hp(10) ratio was 0.7 (Pearson's coefficient $r=0.90, p<0.001$, variation of ratio 0.1–2.3). The variation decreased considerably with increasing Hp(10) ($\sigma 2=0.04$ vs. 0.43 for Hp(10)>0.1 mSv vs.<0.1 mSv, respectively), i.e. higher Hp(10) predicts Hp(3) more reliably.

Moreover, annual Hp(10) data from national dose register during 2009–2018 were used to derive the annual Hp(3) applying the Hp(3)/Hp(10) ratio. The data from Finnish nuclear medicine departments imply that routine measurements of Hp(3) among nuclear medicine technicians are not justified.

Justyna Miszczyk et al 2019, To physically and cytogenetically screen medical personnel of Department of Endocrinology and Nuclear Medicine, Holy Cross Cancer Center, Kielce, Poland (DENM) who are occupationally exposed to 131I.

Materials and Methods:The exposure was monitored by whole-body andfinger ring dosimeters. The thyroid iodine intake was measured by a whole-body spectrometer equipped with two semiconductor gamma radiation detectors. A cytokinesis-block micronucleus assay and the premature chromosome condensation technique were used to assess the aberration score. Cytogenetic analyses were carried out on a group of 29 workers and were compared to 32 controls (healthy donors), matched for gender and age.

Results:On average, the exposed group showed a significantly higher frequency of genetic damage and a higher proliferation index compared to the control group. Smoking status, age and duration of exposure influenced the observed effects in both groups. No differences in

measured biomarkers were observed after stratification of the exposed group into two subgroups based on the measured 131I activity below and above 6 Bq.

Conclusion: The findings suggest that radiation protection principles based on whole-body andfinger ring dosimetry, supported by activity measurements with a whole-body spectrometer, may be insufficient to monitor the absorbed dose estimation of the nuclear medicine staffwho are occupationally exposed to 131I. Furthermore, their future health risks are influenced by confounders. Direct assessments comparing physical and biological dose estimations on the larger group are needed to accurately monitor occupational radiation exposure.

Dutsadee SUTTHO et al dec 2017, Nuclear medicine is the study distribution and localization of the administered radiopharmaceuticals to provide functional or metabolic information. Therefore, patients and staff are subject to radiation exposed. Knowing the radiation from the patients to staff is very important because it leads to workflow and safety . Aim of this study to estimate annual radiation dose to staff per nuclear medicine examination. We measure the radiation dose by pocket dosimeter from 106 patients. 50 patients were measured with bone scan,4 myocardial perfusion,14 venoscintigraphy, 20 thyroid scan, 4 renal function study, 2 lower GI bleeding,7 lung perfusion and 5 TBS after I-131 treatment. At the surface body from the patient, the radiation doses ranged from 79.58±20.4, 42.69±3.94, 34.82±7.11, 27.95±10.00, 4.87±0.95, 4.1±0.85, and <1μSv/hr respectively . The total radiation dose was 99.31 mSv/year . Radiation dose that a worker would have received from the patients can be use as a basis to estimate the radiation dose from the patient to the environment. In addition, these results could be used to modify the process to work and improve staff education.

A. Al-Abdulsalam et al 2013, To investigate radiation exposure among the staff of departments of nuclear medicine (NM) and diagnostic radiology (DR) during 2008 and 2009 and to compare the mean doses received with the limit of 20 mSv/year of the International Commission of Radiological Protection (ICRP).

Materials and Methods:The whole-body dose or effective dose, i.e. Hp(10), and the skin dose, i.e. Hp(0.07), of the staff of departments of NM and DR in Kuwait for the period of 2008 and 2009 were taken from the national thermoluminescent dosimetry database. A total of 1,780 radiation workers, grouped as NM physicians, radiologists, NM technologists, and DR technologists, from 7 departments of NM and 12 departments of DR were included. The annual average Hp(10) and Hp(0.07) were calculated for each group and comparisons were made between the groups and the years. A two-sided Mann-Whitney test was carried out, at the p =

0.05 level, to compare the means. The mean Hp(10) was compared with the limits of the ICRP. Results:Of the 16 distributions of Hp(10) and Hp(0.07), 10 were normal, with a mean annual Hp (10) in 2008 of 1.06, 1.03, 1.07, and 1.05 mSv for NM physicians, radiologists, NM technologists, and DR technologists, respectively. The corresponding Hp(0.07) values for 2008 were 1.03, 1.00, 1.05, and 1.03 mSv, respectively.

Small but significant ($p < 0.001$) reductions in Hp(10) and Hp(0.07) were observed in 2009 for NM technologists and DR technologists. In all other cases, no significant ($p > 0.072$) differences were found. Conclusion:The annual average Hp(10) was well below the limit of the ICRP.

J.Asawarattanapakdee et al 2018 Every type of work performed in a nuclear medicine department will make a contribution to both external and internal exposure of the worker.The purpose of this study is to evaluate the potential risks of internal contamination to staff

members during nuclear medicine practices and to conclude about the requirement of a routine internal monitoring.Following the method describes in the ICRP Publication 78 and the IAEA Safety Standard Series No. RS–G–1.2, in vivo thyroid bioassaysusing NaI(Tl) thyroid probe

were performed to determine the intake estimates on 7 groups of nuclear medicine personnel working with I–131 and Tc–99m, based on working conditions and amount of radionuclides being handled. Frequency of measurements was between 7 and 14 days. These include (1) physicians and physicists, (2) radiochemists (3) technologists, (4) nurses and assistant nurses, (5) imaging room assistants, (6) hot lab workers and (7) hospital ward housekeepers/cleaners. Among all workers, the intake estimates of I–131 in the thyroid ranged from 0 to 76.7 kBq and of the technetium–99m from 0 to 35.4 MBq. The mean committed effective dose equivalent (CEDE) from both I–131 and Tc–99m were 0.63, 1.44 0.53, 0.57, 0.73, 0.98, and 1.36, mSv, for group 1 through group 7 respectively.

However, the highest mean CEDE of 1.44 (max. 1.75) and 1.36 (max. 2.11) mSv observed in groups of radiochemists and hospital ward housekeepers were within the permissible level.

Our results showed that CEDE for internal exposure in this study were less than investigate level of 5 mSv according to the ICRP Publication 78 and the IAEA Basic Safety Standards.

However, the mean CEDE for radiochemists and hospital ward housekeepers were considered in exceed of the limits of recording level (1 mSv). The increasing use of I–131 and Tc–99m in nuclear medicine poses significant risks of internal exposure to the staff. This study suggests that a routine monitoring program for internal exposures should be implemented for most nuclear medicine workers in order to demonstrate that individual doses are kept as low as possible.

Sang-Geon Cho et al 2017 Since the nuclear disaster at the Fukushima Daiichi Nuclear Power Plant in 2011, radiation safety has become an important issue in nuclear medicine. Many structured guidelines or recommendations of various academic societies or international campaigns demonstrate important issues of radiation safety in nuclear medicine procedures. There are ongoing efforts to fulfill the basic principles of radiation protection in daily nuclear medicine practice. This article reviews important principles of radiation protection in nuclear medicine procedures. Useful references, important issues, future perspectives of the optimization of nuclear medicine procedures, and diagnostic reference level are also discussed.

Brígido Flores et al 2019 It is recognized worldwide that the security of radioactive substances is very important and that the design of facilities where these sources are used and stored must cater for the implementation of good security measures, including the shielding of some treatment and diagnostic rooms. The radiation protection assessment of a nuclear medicine facility consists of the evaluation of the annual effective dose both to workers occupationally exposed and to members of the public. This assessment take into account the radionuclides involved, the facility features, the working procedures, the expected number of patients per year, the administered activity, the distribution of rooms, the thickness and physical materials of walls, floors and ceilings and so on. The assessment results were compared to the design requirements established by the Cuban regulatory body in order to determine whether or not, the nuclear medicine facility complies with those requirements, both for workers and for members of the public. The work presented is useful for facility designer that uses unsealed radionuclides and for the regulatory body.

WY Ho et al 2012 To measure external radiation doses and estimate internal radiation doses (due to the process of radionuclide injection) to staff members working in a nuclear medicine department over a 1-year period; to assess the possible radiation doses to staff members in order to determine whether classification of radiation workers is necessary.

Methods: Radiation doses to 4 nuclear medicine physicians, 8 radiographers, and 2 laboratory attendants were measured by digital pocket dosimeters.

Results: After correction for background natural radiation dose, the mean annual radiation dose to the physicians was 0.29 ±0.21 mSv. This was lower than the mean annual radiation dose of 2.07 ±0.97 mSv ($p = 0.017$) to the radiographers and 1.97 ±0.05 mSv ($p = 0.064$) to the laboratory attendants, respectively. The mean radiation dose to the radiographers performing data acquisition and radionuclide injection (1.82 ±1.08 mSv) was not different from that of the radiographers performing data acquisition only (2.53 ±0.47 mSv) [$p = 0.439$]. An empirical formula was applied to compute the possible risk of receiving an internal dose in the process of radionuclide injection. The annual internal radiation dose to individual staff members performing radionuclide injection was estimated to be 0.01 mSv, which can be considered negligible in an estimation of total effective dose.

Conclusions: This 1-year study showed that effective radiation doses to nuclear medicine department staff members were within permissible levels, and that the classification of radiation workers is unlikely to be necessary in a typical nuclear medicine department in Hong Kong.

Fred A. Mettler, et al 2020 Comprehensive assessments of the frequency and associated doses from radiologic and nuclear medicine procedures are rarely conducted. The use of these procedures and the population-based radiation dose increased remarkably from 1980 to 2006.

Purpose: To determine the change in per capita radiation exposure in the United States from 2006 to 2016.

Materials and Methods: The U.S. National Council on Radiation Protection and Measurements conducted a retrospective assessment for 2016 and compared the results to previously published data for the year 2006. Effective dose values for procedures were obtained from the literature, and frequency data were obtained from commercial, governmental, and professional society data.

Results: In the United States in 2006, an estimated 377 million diagnostic and interventional radiologic examinations were performed. This value remained essentially the same for 2016 even though the U.S. population had increased by about 24 million people. The number of CT scans performed increased from 67 million to 84 million, but the number of other procedures (eg, diagnostic fluoroscopy) and nuclear medicine procedures decreased from 17 million to 13.5 million. The number of dental radiographic and dental CT examinations performed was estimated to be about 320 million in 2016. Using the tissue-weighting factors from Publication 60 of the International Commission on Radiological Protection, the U.S. annual individual (per capita) effective dose from diagnostic and interventional medical procedures was estimated to have been 2.9 mSv in 2006 and 2.3 mSv in 2016, with the collective doses being 885 000 and 755 000 person-sievert, respectively.

Conclusion: The trend from 1980 to 2006 of increasing dose from medical radiation has reversed. Estimated 2016 total collective effective dose and radiation dose per capita dose are lower than in 2006.

Chapter Three

Material and Methods

3.1 Materials:

PET/CT Discovery 710 (GE healthcare, USA). The PET system detector material was composed of cerium-doped rare-earth scintillator lutetium-yttrium oxyorthosilicate (LYSO) with block dimensions 9 x 6 mm^2). A CT 64 slice facility with constant tube voltage of 120 kVp was used, the tube current time product (mAs) ranging between 3.0 to 60 mAs. The CT also has Adaptive Statistical Iterative Reconstruction (ASiR) technology, which can allow radiation dose reduction during image acquisition by facilitating pixel noise reduction depending on patient characteristics (patient size) and clinical indications.

Figure 3.1: Siemens Orbiter 37 Gamma camera single head

Figure 3.2: Mediso gamma camera dual head

3.2 Place and duration of study:

The data were collected from Nilain Diagnostic centre and National Centre for Radiotherapy and Nuclear medicine in Sudan and King Faisal Specialist Hospital and Research Canter (KFSH&RC) in the Kingdom of Saudi Arabia, in period from September 2016 till march 2021.

3.3 Methodology:

Annual occupational exposure levels were evaluated for 32 members of staff (6 females and 26 males) at the radiology department of King Faisal Specialist Hospital and Research Center (KFSH&RC) in Riyadh. The hospital is equipped with 20 X-ray machines, covering a range of modalities, as illustrated in Table 3.1. The procedures performed in the department include routine radiography and special procedures with contrast medium (hysterosalpingography (HSG), micturating cystourethrography (MCU), biobsy, urethrography,etc). During routine procedures staff are always required to stand behind a leaded barrier, while for urethrographic and HSG procedures the radiologist usually stands beside the patient in the X-ray room, enabling performance of the manipulative procedures that are required.

3.4 Radiopharmaceutical adiminstration

The ^{18}F radiotracer was produced at the KFSH&RC cyclotron, use also being made of a dose calibrator incorporating a 43.8 cm x 17.2 cm ionization chamber (CRC-55t, CAPINTEC, INC, USA), giving accuracy and linearity within ± 2%. The dose calibrator has automatic background radiation subtraction capability, providing for accurate dose estimation.

Prior to radiopharmaceutical administration, patients were advised to fast for 6 hours. The ^{18}F-Fludeoxyglucose ($C_6H_{11}{}^{18}FO_5$) FDG was then administered intravenously using an automatic injector model Posijet (Lemer Pax , France), providing reasonable protection for staff against ionising radiation at dose rates < 15 μSv/h at 5 cm from the injector walls (with 37 GBq of FDG). ^{18}F emits β+ with $T_{1/2}$ 110 min and a Γ (decay constant) equal to 0.3 Gy/hr/kBq) at 0.01m distance. Images are acquired one hour post radiopharmaceutical injection (allowing for uptake time). The average time per procedure is 30 min.

3.5 Protocol and technique:

Prior to radiopharmaceutical administration, patients were advised to fast for 6 hours. The ^{18}F-Fludeoxyglucose ($C_6H_{11}{}^{18}FO_5$) FDG was then administered intravenously using an automatic injector model Posijet (Lemer Pax , France), providing reasonable protection for staff against ionising radiation at dose rates < 15 μSv/h at 5 cm from the injector walls (with 37 GBq of FDG). ^{18}F emits β+ with $T_{1/2}$ 110 min and a Γ (decay constant) equal to 0.3 Gy/hr/kBq) at 0.01m distance. Images are acquired one hour post radiopharmaceutical injection (allowing for uptake time). The average time per procedure is 30 min.

All PET radiopharmaceuticals are prepared at KFSH&RC (Fig. 3.3). Table 3.1 lists the equipment used in this study. 2.2. Personnel radiation dosimetry Personnel exposures are routinely monitored using calibrated lithium fluoride based TLD-100 thermoluminescence detectors (Zeffective = 8.14, ρ ≈ 2.635 g/cm3), (Harshaw-Bicron, USA). The TLD100 offers a number of favourable characteristics including reasonable resistance to corrosion, low

fading, an acceptable detection limit and reasonable sensitivity for different and mixed radiation energies. To correct for variation in TL signal response (measured in nC), an Element Correction Factor (ECF) was obtained for each individual chip, in accord with equation (1). ECF = Q Q average (1) where Qaverage is the mean signal (nC) from a TLD group under use and Q is the individual TLD signal. The TLD detectors were calibrated using a uniform photon beam from a137Cs source located at the KFSH&RC Secondary Standard Dosimetry Laboratory (SSDL). TLD cards, usually worn by workers during working time in the department, were calibrated to measure dose in terms of the operational quantities Hp(10) and Hp (0.07), considered the most appropriate personal dose equivalent quantities for monitoring of occupationally exposed individuals. Hp (10) measures the deep dose equivalent to the whole body 10 mm beneath an indicated area of the body while Hp (0.07) measures skin dose at 0.07 mm beneath the body surface. Extremity radiation doses were measured using ring dosimeters. Finally, readout of the calibrated TLDs was carried out using an automated TLD reader (Harshaw 6600) supported by Windows-based Radiation Evaluation and Management System (WinREMS) software. The reader stability delivers to better than 1 μGy, linearity < 1% deviation and repeatability 2%. TL signal from background radiation exposure was deducted from the occupational dose. To acquire glow curves the detectors heated up to 240 °C with heating rate 10 °C/s. A 100 °C preheat temperature eliminates post irradiation fading. Post readout annealing was performed using an automatic TLD oven (TLDO; RadPro International GmbH, Germany), the cycle according with manufacturer recommendations of 400 °C for 2 h and 100 °C for 10 min. Patient dose measured from TLD reading (D) was calculated using the flow equation = × D ECF TL signal (nC) RCF (2) where RCF is the Reader Calibration Factor and ECF is the Element Correction Factor. In addition, the hospital Nuclear Medicine department is equipped with the following tools: a radiation monitoring system, radiation monitoring equipment, personal dosimeters, Geiger

counters and a hand-foot monitor. Special tools and equipment used to reduce exposure in the department include: Dose calibrator with a thick shield, an extra thick lead-block table, tungsten syringe shield, extra shielded syringe carriers and shielded carts for transport (Fig. 3.3). Radiopharmaceuticals injection was performed routinely using automatic injector for 18F-FDG. However, in many cases manual injection was used because the automatic injector was inoperative. The remaining radioisotopes are usually manual injected. Radiologic technologists exchange their duties in injection and imaging room every day. Three waiting rooms are available with fixed shielding while the third waiting area shielded with mobile shield.

3.6 Effective radiation dose evaluation in nuclear medicine examination

All data were collected from two nuclear medicine departments: Al-Neeleen Medical Diagnostic Center ((NDC) Private Center) and Radiation Isotope center (RICK- public center) in Khartoum Sudan. A total of 130 procedures were performed in NDC (40 cardiac scan, 46 thyroid scan and 40 bone scan) and investigated using a gamma camera (single-head) (Orbiter – Scintron 37) manufactured by Siemens, Medical Imaging Electronics (MiE), Erlangen, Germany). The gamma camera unit has a 387 mm field of view (FOV) and 37 photo multiplier tubes (PMTs). 99mTc is the radionuclide of choice for many nuclear medicine examinations due to is suitable photon energy (0.140 MeV) and reasonable half-life (6.0 hrs) (Figure 3.1). A total of 63 procedures were performed in RICK (22 bone scan, 21 thyroid scan, and 20 renal scan) using the Nucline Spirit, Mediso γ camera with dual head and low energy collimator, a Nal (Tl) crystal, a light guide and an array of photomultiplier tubes (PMTs) . The Nal (Tl) scintillating crystal has 9.5 mm thickness and dimensions of 59 x 47 cm (Figure 3.2). The data of this study were collected from the patients' administrated activities (AAs) (MBq) and patients' demographic data (age, weight and BMI) and used to evaluate the imaging protocol to ensure optimum image quality. The administered activity to

each patient was calculated using the following equation: Bone Scan examination The Radiopharmaceutical used for the bone scan procedure was 99mTc Methylene Diphosphonate (MDP) with gamma-ray energy 140keV and the administered activity (9mTc – MDP) ranging from 15 mCi (555MBq) to 20 mCi (740 MBq) which was administered intravenously with an uptake time for imaging of about at least 150 min post injection. In order to obtain proper image, patients prepared for the nuclear medicine imaging procedure by drinking 1 litter of water after administration of radiopharmaceutical. Urination is necessary prior image acquisitions stage to improve image quality (Christian et al., 2012). Scan of urinary system 99mTc-DTPA is a radiopharmaceutical used for renal scan to assess the kidney function with gamma ray spectrum of about 140 keV and the administered activity of around 5- 10 mCi (185-370MBq). The patient should be injected with 10 mCi of DTPA to focus on the urinary system in a portable study. In cases of kidney failure, the aorta is used as a reference point. The image is taken immediately after administrated activity. Patient is placed in a supine position with the camera at the posterior. The patient is allowed to drink water 30 minutes prior the study (Christian et al., 2012). Endocrine System scan The radionuclide 99mTc Pertechnetate is used to assess the function of the endocrine system. The maximum administrated activity is about 370 MBq for adult. The time of imaging is about 20 minutes post injection (Shackett et al., 2009).

3.7 Fluoro-D-glucose (18F-FDG) PET/CT and patient dose

The data used in this study were collected at King Faisal Specialist Hospital and Research Center (KFSH&RC), Riyadh. The hospital is considered a national referral centre and is the largest hospital in the region. The institutional review board (the effective Ethics committee) permitted the study, the data being collected and processed according to the institutional ethical guidelines. A total of 636 procedures were performed in KFSH&RC over a period of 6 months, from April to September 2018, comprising 187 lymphoma, 82 nasopharyngeal

carcinoma, 30 thyroid and 337 other cases). The data were collected in accord with a checklist concerning the administrated activities (AAs) (in MBq) and effective dose (in mSv) for a standard sized adult patients (i.e. 70 ± 10 kg) for a standard procedure, sufficient to obtain the optimum diagnostic information. The effective dose (E) resulting from ^{18}F-FDG administration was derived using Radiation Dose Assessment Resource (RADAR) software based on radiopharmaceutical biokinetic models (Stabin & Siegel, 2018):

$$E = \sum_T W_T \times H_T \qquad (3.1),$$

with W_T the organ or tissue weighting factor and H_T equivalent dose (mSv).

External effective doses from CT were estimated using the dose-length product (DLP) in mGy·cm as illustrated in equation 1 using NRPB and ImPACT CT Dosimetry software (version 1.0.4) (NRPB-SR250,1996, ImPACT, 2011):

$$E = k \times DLP \qquad (3.2)$$

with k a conversion factor based on tissue or scanned organs.

The radiogenic risk (R_T) per PET/CT examination was obtained in accord with equation 3:

$$R_T = F_T \times E \qquad (3.3),$$

with F_T the radiation induced cancer risk coefficient, equal to 5.5 Sv^{-1} for the general population and E the radiation effective dose (mSv) per procedure (ICRP, 2007).

3.8 Radiation dosimetry

The occupational radiation doses received by the nursing staff, medical physicists and radiologists were measured and analysed over a one-year period. The total number of workers were 30, including Radiologic Technologists (RT), RTs handling and dispensing the radiopharmaceuticals. The availability of modern hybrid equipment (PET/CT, SPECT/CT and SPECT) within the department enables performance of all the investigations of interest,

use being made of the wide variety of radiotracers available (Table 3.2). Prior to imaging patients were suitably prepared, as an instance fasting for 6 h before some examinations, in particular those involving FDG. Administered activities of up to 7.4 MBq/kg were used, with a total activity range from 370 to 1110 MBq. In order to enable reasonable uptake of the radiopharmaceutical, image acquisition typically starts 1.0 h post administration. All patients in the study, taking place from January 2018 to December 2018, were referred to the nuclear medicine department as a result of clinical indications that were justified by competent practitioners. Ethics and research committee approval was obtained for the study.

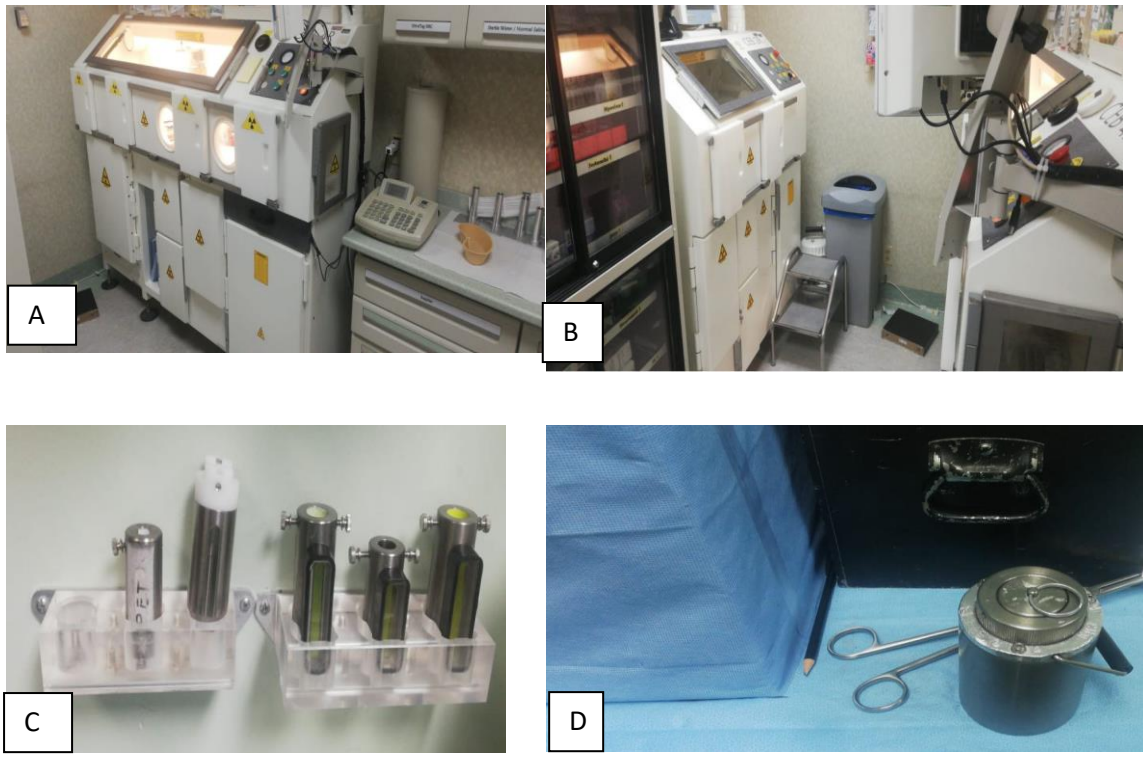

Figure 3.3 . Nuclear Medicine dose preparation area A: Preparation area for Tc-99m ,B: Preparation area Ga (Gallium),C : Syringe shield& D: Vial shield

3.8.1 Staff radiation dose and estimated risk in an interventional radiology department

3.8.2. Occupational dosimetry

Staff exposures were measured using TLD-100 thermoluminecent dosimeters, formed of LiF:Mg,Ti (Harshaw-Bicron, Solon, Ohio USA). TLD-100 has wide dynamic measurement range, from 10.0 ipGy to 10.0 Gy, linear from 0.01 mGy to 1.0 Gy and low in the rate of fading, at ≤ 5% over a three-month period post irradiation. These features are among those making it suitable for occupational dosimetry. Prior to clinical use of the TLDs, all of the chips were irradiated to an equal dose in order to evaluate their sensitivity to radiation, use being made of a 137Cs source, the process being conducted three times in seeking to accurately establish the sensitivity factor (providing individual element correction factors, Fs). The sensitivity factor for each chip was obtained by dividing each TL signal (measured in nC) by the mean signal of all of the irradiated TLDs (TLaverage), as illustrated in equation (3.4):

$$F_S = \frac{Tl}{Tl_{average}} \qquad 3.4$$

The TLDs were subsequently calibrated under reference conditions (ISO, 1991) at a Secondary Standard Dosimetry Laboratory (SSDL), calibrated for the personal dose equivalent (Hp (d)) (in mSv) at specific depths d (in mm) for deep organs dose, Hp (10), and shallow dose, Hp (0.07). Measurements were based on use of the Harshaw two chips card holder 8814, with the TLD-100 chips inserted into aluminium cards fixed within holders. TL signal readout was carried out using a calibrated Harshaw 6600 TLD reader, the background TL signal being subtracted from all readings. With this Hp (d) was obtained in accord with equation (3.5), as follows:

$$H_p(d) = \frac{F_S \times TL\ \text{signal(nC)}}{R_{CF}} \qquad 3.5$$

with RCF the calibration factor for the TLD reader.

The readout time-temperature profile consisted of 100 °C preheat temperature, glow curve acquisition temperature 100 °C–240 °C at a heating rate of 10 °C/s. The TLD chips annealing cycle was 400 °C for 2 h and 100 °C for 10 min, carried out using a RadPro TLD-oven (RadPro International GmbH, Wermelskirchen, Germany).

3.8.3. Personal dose assessment

The operational quantities for personal dose equivalent were collected for two consecutive years 2017 and 2018. The TLD cards are usually worn at collar level with an appropriate filter to provide measurement of personal dose equivalent Hp (d) over the lead apron. Staff doses were compared against the occupational dose limits recommended by the International Commission on Radiological Protection (ICRP, 1991). These limits are typically adopted and used by regulatory authorities, seeking to prevent tissue reactions and to decrease the incidence of stochastic effects; the recommended annual dose limit is 20 mSv/year for the whole body, averaged over five years. The effective dose (E) is given by equation (3.6), as follows:

$$E(mSv) = \sum_T W_T H_T \qquad 3.6$$

where HT is the equivalent dose to an organ or a tissue (T) and WT are tissue weighting factors, as detailed by the ICRP (ICRP, 2007). The cancer risk is calculated by multiplying the effective dose (mSv) by the cancer risk factor (5.5% Sv-1) as stated by the ICRP (ICRP, 2007).

3.9 Occupational and ambient radiation exposure from during targeted 177 71 Lu Therapy

Radiopharmaceutical Administration: The study, which was carried out over a period of 11 months at King Faisal Specialist Hospital and Research Center (KFSH&RC), encompassed a total of 33 patients who received Lutetium-177 therapy, all. Patient radiation dosimetry was evaluated using a standard administered activity of 177Lu DOTATATE for therapy (Figure 3.4). The mean, standard deviation and range of admistered activity (in GBq) were 7.115 ± 0.917 (4.329 -7.955). Inclusion criteria were for patients with progressive unrespectable meningioma, or refusal of surgery. Positive Somatostatin receptor type 2 (SSTR2) status was assessed by a 68Ga DOTATOC/DOTATATE PET scan and quantified by the maximum Standardized Uptake Value (SUV). Exclusion criteria included: Preexisting grade II–IV hematologic/renal toxicities 6, Karnofsky performance status less than 50 (WHO grade 3 or 4), pregnancy and breastfeeding or also serious forms of concomitant illness, such as advanced psychological problems. Complete or partial response, stable disease, disease progression, according to Response Evaluation Criteria in Solid Tumors (RECIST) criteria) as well as toxicity, are secondary endpoints (Gehan and Tefft, 2000). Radiopharmaceuticals preparation and treatment protocol 177Lu-DOTATOC/DOTATATE from IDB/ITG was prepared as per Eckert & Ziegler generator (Eckert & Ziegler, 2016) (Figure 3.5). Quality control was performed using reverse-phase high-performance liquid chromatography on a Phenomenex Jupiter C18 5 mm, 250 · 4.6 column (eluents, 0.1% trifluoroacetic acid and 5 acetoni-trile; flow, 0.75 mL/min; gradient, 0–25 min; 95%–50%). Long-acting somatostatin analogs were withheld for at least 4 weeks and short-acting somatostatin analogs for at least 3 days before 177Lu- DOTATOC/DOTATATE therapy. 20 mg of intravenous dexamethasone was administered before therapy. Amino acid solutions containing lysine and arginine was administered before and after 177Lu-DOTATOC/DOTATATE injection to inhibit tubular

reabsorption for renal protection. All patients were treated with 7.4 MBq (200 mCi) of 177Lu-DOTATOC/DOTATATE diluted in 50 ml of normal saline for 30 min slow infusion. The treatment was repeated every 6 to 8 weeks for a minimum of 4 cycles. Treatment was stopped in case of severe toxicity as assessed by Common Terminology Criteria for Adverse Events (CTCAE) (CTCAE, 2010). Imaging and Follow up evaluation During hospitalization, clinical status and vital signs were monitored before and for 72 hours after each therapeutic cycle. After administration of the radiopharmaceutical, image acquisition was performed promptly, 24 hours subsequently and on day three and seven using a SPECT-CT Symbia Siemens T16 CT Slices facility (Siemens Healthcare, GmbH, Germany) (Figures 3.6 & 3.7). After discharge, blood chemistry and hematologic parameters were measured at biweekly intervals. Imaging included a baseline 68Ga-DOTATOC/DOTATATE positron emission tomography (PET) scan and magnetic resonance imaging (MRI) performed 2 to 4 weeks before treatment and 4 to 8 after treatment. Follow-up clinical and radiological examinations were performed every 3 to 6 months depending on neurological status. Response evaluation was conducted according to RECIST Criteria (Gehan and Tefft, 2000). Ambient and occuational exposure measurement Ambient and Occupational exposure was estimated based on measurements made at separations of 30 cm, 100 cm, and 300 cm, also behind a bed shield used during the period of patient hospitalization. Use was made of a calibrated survey meter (Victoreen 451P, Fluke Biomedical). Occupational and ambient doses were measured using calibrated thermoluminescent dosimeters (TLDs) supported by an automatic TLD reader (Harshaw 6600). The 177Lu-DOTATOC/DOTATATE was carefully handled to minimize radiation exposure to the operators, proper use being made of radiation shielding and disposable waterproof gloves to prevent cross contamination. All radiation protection measures were evaluated by an experienced and certified radiation safety officer. Ethical permission for the study was obtained from the institutional review board (IRB) as well as all

patients undergoing the procedures, all of whom were receiving the treatments for clinically justified reasons; no volunteer were involved.

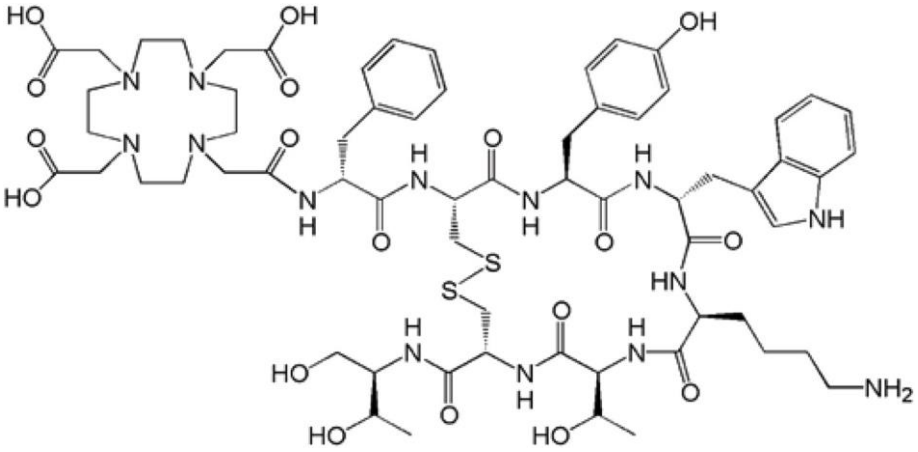

Fig..3.4 Lu-177–DOTATOC chemical composition.

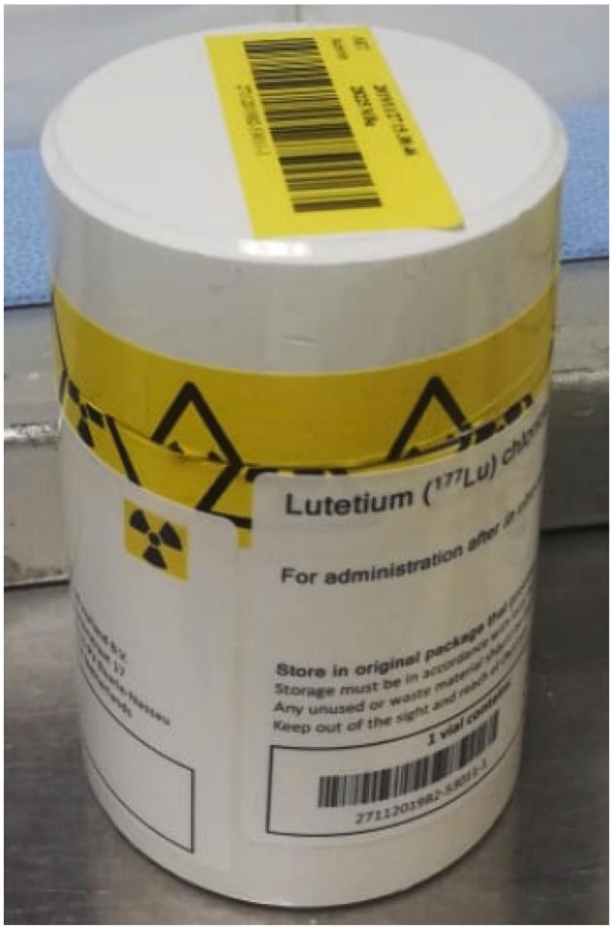

Fig. .3.5 177Lu-DOTATOC/DOTATATE from IDB/ITG in a vial shield.

Fig. 3.6 SPECT-CT symbia siemens 16 CT slices.

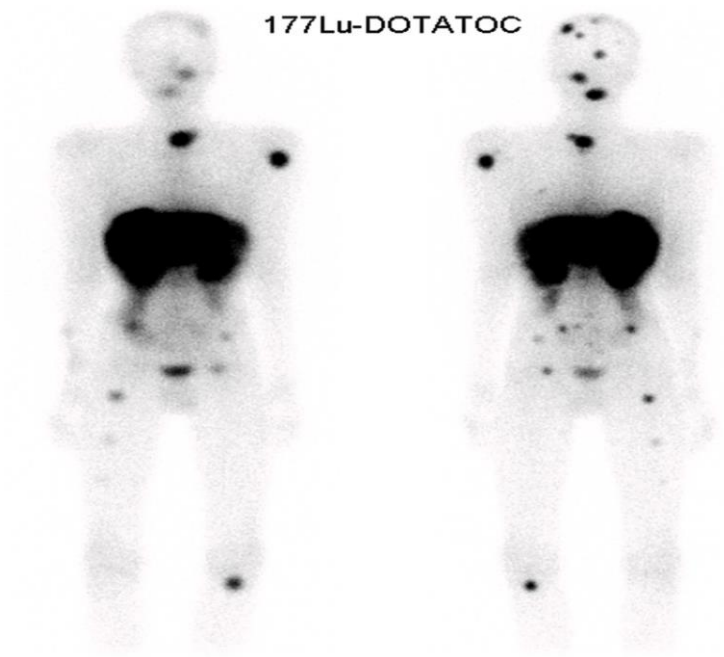

Fig. .3.7. 1st cycle of Lu-177 -Dotatate treatment after 24 h.

3.10 Occupational Exposure and radiobiological risk from thyroid treatment with radioiodine -131

Occupational exposure was measured for six personnel during a total of 182 (138 (75.8%) females and 44 (24.2%) males) patients, who undergone thyroid cancer therapy with radioiodine (^{131}I) during one year at King Faisal Specialist Hospital and Research Center (KFSHRC) (Table 1) . The KFSH&RC is one of the main referral centers for thyroid cancer treatments with radioiodine in the Kingdom of Saudi Arabia (KSA). Ethics and Research Committee at KFSH&RC center approved the research and consent was obtained from each patient's prior data collection. Patients data include age, weight and body mass index (BMI, kg/m^2)) in addition administered activity and exposure geometry were quantified.

3.11 Patient populations and radioiodine administration

Radioiodine therapy was performed using oral administration of capsules. Each Radioiodine capsule contain sodium thiosulphate ($Na_2O_3S_2$) and disodium sulphate (Na_2O_4S) (Figure 3.8). ^{131}I was administered at the patient's hospital beds. The patient was asked to sit at a table covered with adsorbent pads and the floor beneath the patient was also be covered by adsorbent pads. The ^{131}I is administered in capsules in a shielded (>1 cm Pb) container. The patient was advised to drink several glasses of water to clean the mouth. Thyroid uptake and imaging is carried out within 24 hours. Patient discharged when the dose-rate at a distance of 1m from the treated individual is not exceed 25 μSv/h.

3.11.1 Isolation ward

A nuclear medicine department which uses ^{131}I as a radioactive source for treatment needs the patients to be admitted in wards for some days and their waste product is drained into separate waste management facility which is called delay tank. There will be significant amount of radioactive waste generated from the patient. Almost 70 % of 131I can be excreted

in urine from the patients within three days after administration (Leung and Nikolic, 1998). Patients treated with radioiodine 131 remained in isolation for a period of 3 days in 6 isolation rooms are available to protect public from radiation exposure. During isolation period, waste is drained into isolated delay container. At the department and each patient in separate room. All radiation protection policy performed according to the national and international recommendations for occupational and public dose limits. The maximum annual exposure for staff working in radiation field (expected to receive annual effective dose ≥2.0 mSv,i.e ≥10% of the permissible dose limits) including medical physicist, physicians, technologist and nurses is 20 mSv/year, and 100 mSv for five next years, while 50 mSv is the maximum dose for a single year. Annual dose for general public (visitors and comforters) is limited to 1.0 mSv (ICRP 60, 1991). In nuclear medicine department, infants and children are not allowed access to the ward area. There are no dose limits to the patient at this time for medical procedures. It is well known that there are no patients dose limits for justified medical procedures.

3.11.2 Staff contamination assessment

Occupational exposure to radioiodine may results in accumulation of radioiodine in the thyroid. The international Atomic Energy Agency recommended staff monitoring if the potential committed annual effective doses ≥1 mSv ().The Thyroid uptake was performed to all personnel to evaluate the radioiodine concentration. The procedure was performed in a Sitting position with the detector field of view placed at the neck level. Thyroid activity from radioiodine contamination was quantified using thyroid uptake measurements for all staff (one medical Physicist and six nursing staff. Ambient doses were measured at wall 1.5 m Height. Patient's exposure was estimated based in measured on radioactivity at 30 cm, 100 cm and 300 cm during hospitalization using calibrated survey meters (Victoreen 451P, Fluke

Biomedical). Absorbed dose (D) to thyroid reuslted from 131I adimistered activity (A) was calculated fusing the following eqution

$$A\ (MBq) = \frac{23.4 \times m(g) \times D(Gy)}{U \times T}$$

Where m is the thyroid mass in gram, U is the thyroid dose uptake and T is the effective half-life of radioiodine.

3.11.3 Occupational exposure dosimetry

Occupational exposure for radioiodine treatment personnel was measured using two groups of thermoluminescent detectors (TLD-100). The TLDs were at the level of the chest above the lead apron (0.5 mm thick lead equivalent), and the second at the level of the waist under the lead apron. Extremity doses were measured using ring dosimeters placed on the right hand of the operator. TLD 100 was manufactured by Harshaw-Bicron Company, USA. TLD-100 used in this study for their capability in accurate radiation dose measurement for a wide range of dose values from few µGys to many Gys (10^{-7} Gy to 12 Gy). Low fading is important characteristic for personal dosimetry, which enabled dose measurement in two month intervals in routine department work. ATLDs were calibrated at the Secondary Standard Dosimetry Laboratory (SSDL) using cesium-137(^{137}Cs) radioactive source located at the KFSH&RC for TLD cards for calibration occupational exposure (mSv) in terms of skin dose (Hp (0.07)) and deep dose (Hp(10)). All TLD signals were acquired using TLD reader (Harshaw 6600) (Harshaw-Bicron Company, USA). The time temperature profile used consist of 100 0C preheating and signal acquisition up to 240 ^{0}C at heating rate 10^0C/s. Pre and post irradiation annealing was applied for all TLDs batch using automatic Oven(TLDO; Germany) according to the manufacturer recommendations.

3.11.4 Ambient dose and patient room measurement

Ambient dose measurement was performed using calibrated TLDs (TLD-100) at certain locations at radioiodine therapy department including nursing station (reception) and corridor of the department which all patients room opened in it. In addition to that radiation dose measurements were carried out at patients' room at the following locations including toilet, bed basin using survey meter (Victoreen 451P, Fluke Biomedical)

Figures 3.8. A&b: Radioactive iodine

Chapter Four

Results

A total of 193 nuclear medicine procedures were performed in the present work to establish the Administrated Activity (AA) and the effective dose in Sudan. The mean AAs and effective dose correlated with the results of scientific papers published in international literature. In this study, for cardiac patients with an average range of 73.8±13 kg, the Administrated Activity (AA) in Mega Becquerel (MBq) was about (810±246 MBq) and the effective dose in milli Sievert (mSv) was about (7.1±2 mSv).While for bone scan patients with size range of 64.8±19.6 Kg, the AA was about (796.8±58.2 MBq) and the effective dose was about (4.6±0.31 mSv). Although for thyroid scan with mean patient size of 63.8±15.1kg, the AA was (195.1±21.2 MBq) and the effective dose was about (2.6±0.27 mSv). Finally for renal study with average patient weight of about 67.3±28.1 kg, the AA was about (198.6±32.9 MBq) and the effective dose was (0.97±0.16 mSv) (Tables 4.1 and 4.2) and (Figure 4.1 and 4.2). As shown in Table 4.3, there is quite a distinction between Administrated Activities given by countries except in Brazil which has higher dose in bone and thy roid scan compared with other countries. The results of Administrated Activities in our studies in (Table 4.3) and (Figure 4.3) regarding the average AA in (MBq) of different types of diagnostic examinations was compared with a surv ey from other countries (Vogiatzi, et al., 2011; Bomben et al., 2004; Khoury etal, 1994; Flores et al., 2006; Papadopoulos et al., 1990; Lai et al., 1995; Mettler et-al., 1986; DRL Japan, 2015).Table 4.4 and Figure 4.4 shows the range of radioisotope administrated activities and the administrated activity for Sudanese. It is mentioned that the Sudanese AAs is within the values of (IAEA, 1996; ARSAC, 2006; EC, 1999; SSK, 2000) except for (RSNA, 2008) 99mTc-DMSA for renal scan, 99mTc-MDP/HDP for bone scan,99mTc- Tetrofosmin for Cardiac scan and TcO4

for thyroid scan when the administrated activities value was increased. That means the Sudanese administrated activity is within the tolerance value of international literature. In (RSNA, 2008), the AAs is increased to approximately one and half the AAs used in Sudan for cardiac scan. When compared with (EC, 1999; SSK, 2000), there was observed increase in mean dose in Sudanese Administrated Activities. One of the main objectives of this study was to progress a national database of patient dose in diagnostic imaging in view of establishing the Administrated Activities in Sudan. Also the study was conducted under the real clinical settings and did not consider the potential factors that might affect the dose measured namely exposure parameters and performance of the machine. This survey was narrowed to adult patients with age greater than 16 years in nuclear medicine. For nuclear medicine, it is recommended that the medical facilities in the country adopt these administrated activities and effective dose as guidance in order to compare with their local practices. If doses exceed these a review is considered to guarantee effective protection of the adjusted patients while maintaining diagnosable image. Nonetheless, if the administrated activities and effective dose are exceeded, this does not essentially mean that the investigation has been unsuitably conducted. Exposures beyond the level might be beneficial in order, for example, to reach image quality which is improved. On the other hand, helpful action should be taken as required if the radiation dose do not afford beneficial diagnostic findings.

Table 4.1: Mean, ±Sd and range of patient demographic data, administered activity and effective dose in Bone, thyroid and kidney in Isotope center					
Exam	No.	Age (y)	Weight (kg)	Activity (MBq)	effective dose (mSv)
Bone	22	(51.9±15.5) (82-24)	(65.8±27.2) (160-30)	(842.4±73.3) (933.1-703)	(4.8±0.42) (5.7-4)
Thyroid	21	(37±7.7) (50-25)	(63.55±13.2) (98-50)	(212.8±26.3) (254.56-152.1)	(2.8±0.34) (3.3-1.97)
Kidney	20	(40.4±14.1) (68-17)	(67.3±28.1) (68-17)	(198.6±32.9) (251.60-155.4)	(.97±0.16) (1.23-0.76)

Table 4.2: Mean, ±Sd and range of patient demographic data, administered activity and effective dose in cardiac, thyroid and bone scans					
Exam	No.	Age (y)	weight(kg)	Activity (MBq)	effective dose (mSv)
Cardiac	40	(57.8±9) (30-82)	(73.8±13) (46-111)	(810.0±246) (740-1665)	(7.1±2) (6.7-13.2)
Thyroid	46	(43.8±14) (19-70)	(64.1±17) (14-93)	(177.4±16) (114.7-192)	(2.3±0.2) (1.5-2.5)
Bone	44	(57.3±10) (36-75)	(63.7±12) (42-75)	(751.2±34) (740-925)	(4.3±0.2) (4.2-5.3)

Table 4.3: Comparison of average administered activity (MBq) of different types of diagnostic examinations with survey from other countries (Adults ≥ 16 years old).

Diagnostic Exam.	Radiopharmaceutical	Average Administered Activity (MBq)									
		NDC	RICK	[22]Argantina	[23]Brazil	[24]Cuba	[25]UK	[26]Greece	[27]Tiwan	[28]USA	[29]Japan
Bone	Tc-99m MDP/HDP	(751.2±34) (740-925)	(842.4±73.3) (933.1-703)	860	1016	740	682	536.5	560	740	950
Cardiac	Tc-99m Tetrofosmin	(810.0±246) (740-1665)	N/A	700	N/A	N/A	N/A	N/A	540	N/A	900
Thyroid	TcO4	(177.4±16) (114.7-192)	(212.8±26.3) (254.56-152.1)	210	426	222	N/A	114.7	80	185	300

Table 4.4: Comparison of average administered activity (MBq) of different types of diagnostic examination with difference recommended DRLs (Adults ≥ 16 years old).

Diagnostic Exam.	Radiopharmaceutical	Average Administered Activity (MBq)						
		NDC	RICK	[15]IAEA 1996	[16]ARSAC 2006	[17]RSNA 2008	[18]EC 1999a	[19]SSK 2000
Bone	Tc-99m MDP/HDP	(751.2±34) (740-925)	(842.4±73.3) (933.1-703)	800	800	1110	600	750
Cardiac	Tc-99m Tetrofosmin	(810.0±246) (740-1665)	N/A	800	800	1500	N/A	N/A
Thyroid	TcO4	(177.4±16) (114.7-192)	(212.8±26.3) (254.56-152.1)	200	80	370	N/A	N/A
Kidney	Tc-99m DMSA	N/A	(198.6±32.9) (251.60-155.4)	160	80	370	80	70

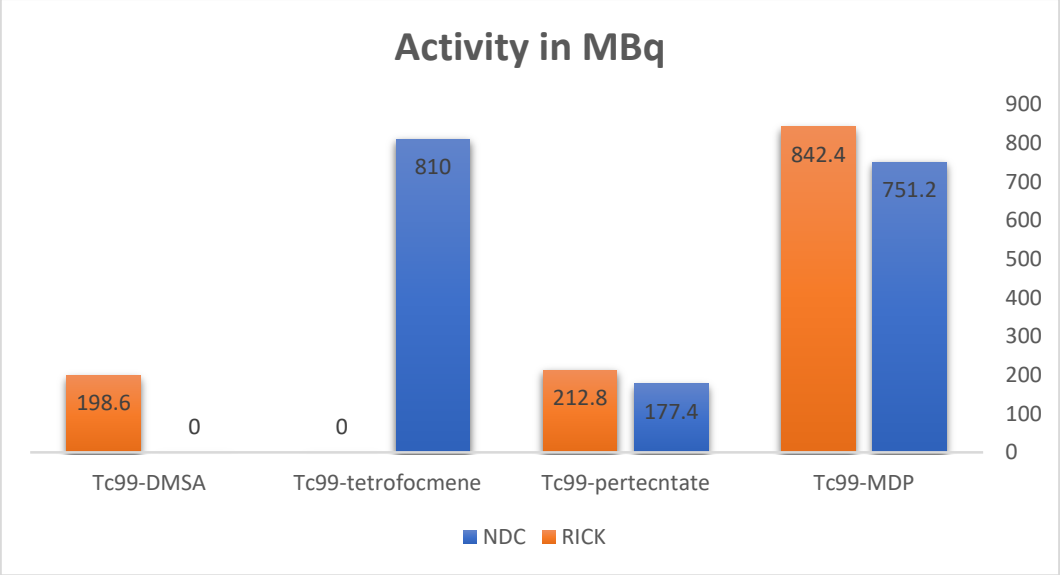

Figure 4.1: the activity comparisons in two medical center in Sudan

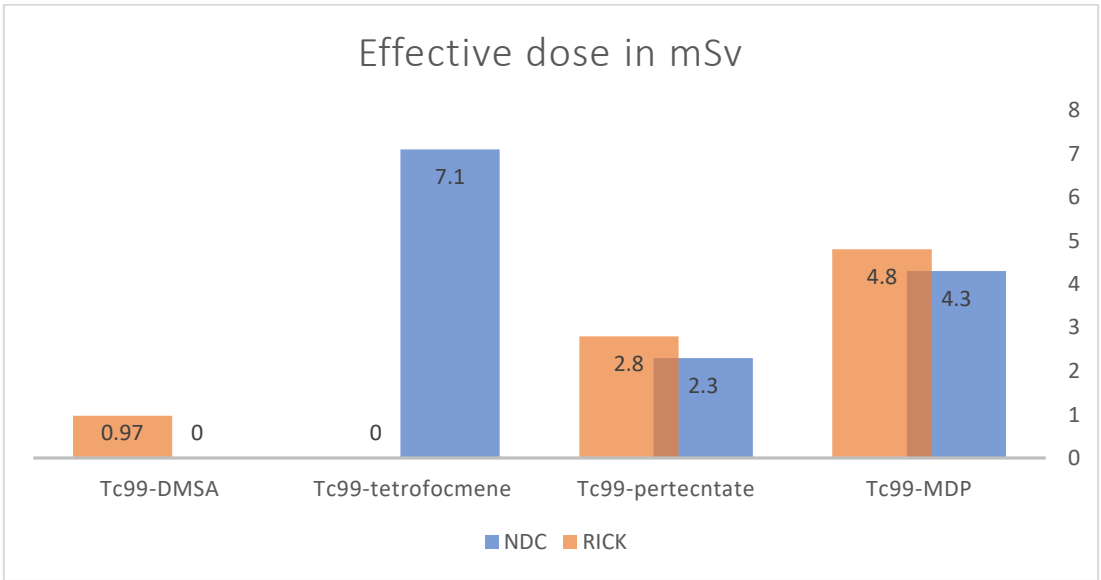

Figure 4.2: the effective dose comparisons in two medical center in Sudan

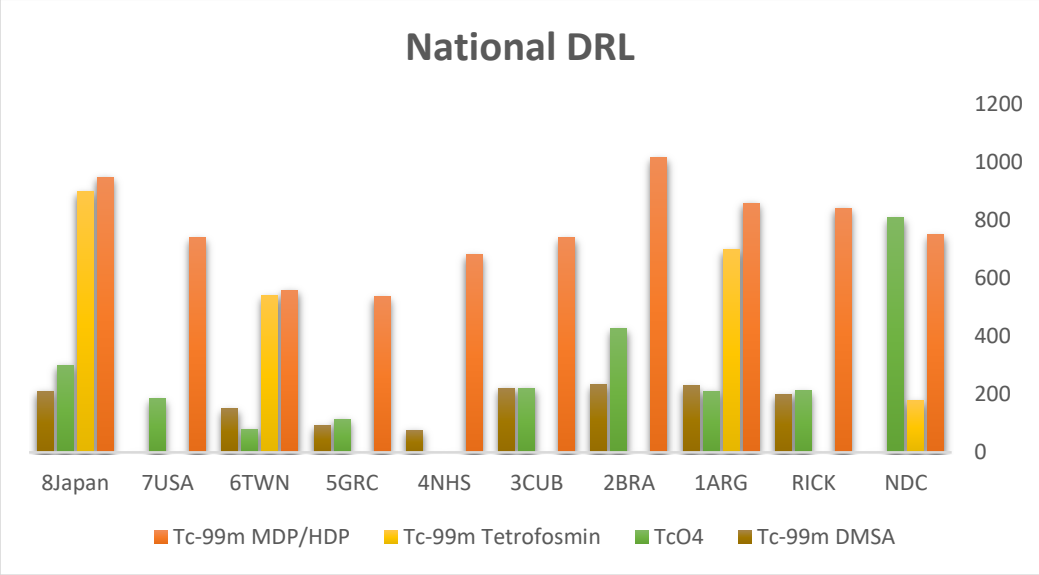

Figure 4.3: the activity comparisons between the local and National DRL

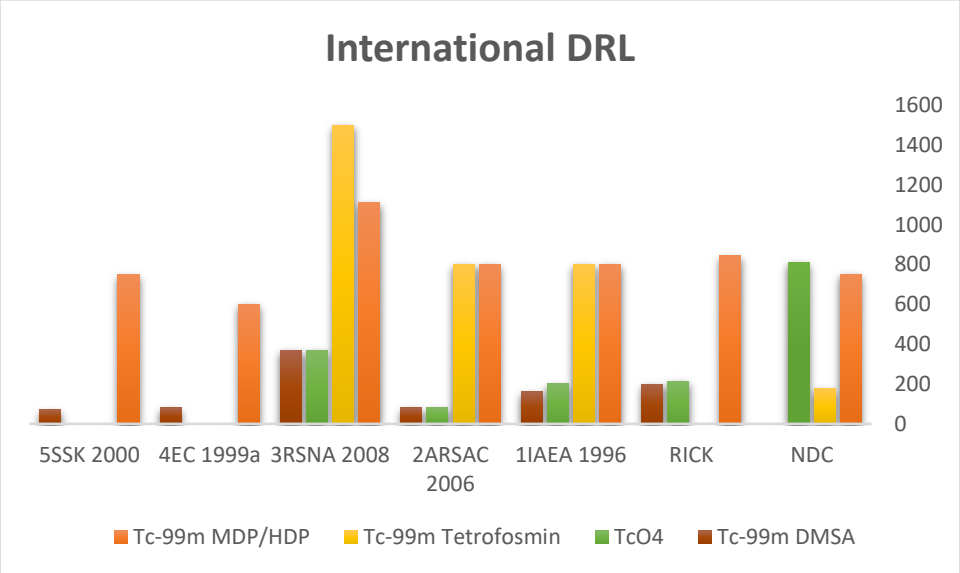

Figure 4.4: the activity comparisons between the local and international DRL

Table 4.5: Mean, ±Sd and range of patient demographic data, administered activity and effective dose for (Lymphoma, Nasopharyngeal carcinoma, Thyroid and others) in PET Scan.

Indication	No. Patient	Age (y)	Height (Cm)	weight (kg)	BMI (Kg/m^2)	Activity (MBq)	effective dose (mSv)
Lymphoma	187	(39.3±16.4) (18-91)	(164.8±11.9) (113-186)	(76.2±24.7) (31-171)	(28.4±12.1) (13.6-133.5)	(433.9±70.6) (297.5-735.9)	(8.2±1.3) (5.7-13.9)
Nasopharyngeal carcinoma	82	(46.4±14.0) (18-83)	(164±9.2) (140-182)	(69.7±17.4) (35-134)	(25.8±5.7) (14.6-44.8)	(417.7±55.9) (325.6-547.6)	(7.9±1.1) (6.2-10.4)
Thyroid	30	(52.3±16.4) (20-81)	(162.5±10.2) (144-179)	(80.1±22.7) (45.2-140)	(30.3±8) (16.8-51.4)	(450.1±71.4) (344.1-566.1)	(8.6±1.4) (6.5-10.8)
Others	337	(54.2±14.9) (20-93)	(160.9±10.34) (135-198)	(71.7±16.4) (36.4-134)	(27.8±6.3) (13.5-58.8)	(421.6±58.3) (283.4-606.8)	(8.0±1.1) (5.4-11.5)

Table 4.6: Mean, ±Sd and range of patient demographic data, administered activity and effective dose for Lymphoma							
gender	No. Patient	Age (y)	Height (Cm)	weight (kg)	BMI (Kg/m^2)	Activity (MBq)	effective dose (mSv)
M	131	(38.73±17.03) (18-91)	(169.14±10.80) (113-186)	(81.96±25.38) (43.5-171)	(29.38±13.73) (16.58-133.92)	(450.61±72.99) (314.5-735.93)	(8.56±1.39) (5.98-13.98)
F	56	(40.59±14.90) (19-71)	(154.75±7.28) (138-174)	(62.76±16.79) (31-133)	(26.19±6.74) (13.59-53.95)	(394.87±45.28) (297.48-536.5)	(7.50±0.86) (5.65-10.19)
Overall	187	(39.7±15.87) (18-91)	(161.9±9.04) (113-186)	(72.4±21.1) (31-171)	(27.8±10.24) (13.59-133.92)	(422.7±59.12) (297.48-735.93)	(8.03±1.13) (5.65-13.98)

Table 4.7: Mean, ±Sd and range of patient demographic data, administered activity and effective dose for Nasopharyngeal carcinoma							
gender	No. Patient	Age (y)	Height (Cm)	weight (kg)	BMI (Kg/m2)	Activity (MBq)	effective dose (mSv)
M	62	(48.16±13.67) (19-83)	(166.91±7.73) (147-182)	(73.35±16.08) (48-134)	(26.29±5.25) (44.77-17.42)	(429.29±56.60) (325.6-547.6)	(8.16±1.08) (6.19-10.40)
F	20	(40.95±14.03) (18-70)	(155.15±7.87) (140-169)	(58.54±16.97) (35-91)	(24.33±6.87) (14.57-35.75)	(381.54±35.49) (347.06-485.81)	(7.25±0.67) (6.23-6.59)
Overall	82	(44.56±13.85) (18-83)	(161.03±7.8) (140-182)	(65.95±16.53) (35-134)	(25.3±6.1) (14.57-35.75)	(405.4±46.1) (325.6-547.6)	(7.7±0.88) (6.19-10.4)

Table 4.8: Mean, ±Sd and range of patient demographic data, administered activity and effective dose for thyroid							
gender	No. Patient	Age (y)	Height (Cm)	weight (kg)	BMI (Kg/m^2)	Activity (MBq)	effective dose (mSv)
M	14	(47.79±19.48) (20-81)	(170.41±6.68) (158-179)	(79.44±21.88) (45.2-130.8)	(27.12±6.19) (16.81-40.82)	(447.86±64.46) (366.3-566.1)	(8.51±1.23) (6.96-10.76)
F	16	(56.19±12.43) (32-76)	(155.5±7.20) (144-165)	(80.68±24.09) (49-140)	(33.15±8.52) (18.90-51.42)	(452.02±79.10) (344.1-562.4)	(8.59±1.50) (6.54-10.69)
Overall	30	(51.99±15.96) (20-81)	(162.9±6.9) (144-179)	(80.1±22.9) (45.2-140)	(30.1±7.4) (16.81-51.4)	(449.9±71.8) (344.1-566.1)	(8.6±1.4) (6.54-10.76)

Table 4.9: Mean, ±Sd and range of patient demographic data, administered activity and effective dose for others							
gender	No. Patient	Age (y)	Height (Cm)	weight (kg)	BMI (Kg/m^2)	Activity (MBq)	effective dose (mSv)
M	166	(54.5±15.41) (21-93)	(167.76±7.19) (150-189)	(73.58±15.62) (42-128.5)	(26.12±5.22) (16-44.96)	(426.83±56.18) (338.92-580.9)	(8.11±1.07) (6.44-11.04)
F	171	(53.91±14.56) (20-83)	(154.27±8.43) (135-198)	(69.80±16.88) (36.4-134)	(29.35±6.89) (13.49-58.77)	(416.48±60.06) (283.42-606.8)	(7.91±1.14) (5.38-11.53)
Overall	337	(54.2±14.9) (20-93)	(161.0±7.81) (135-198)	(71.7±16.3) (36.4-134)	(27.7±6.1) (13.49-58.77)	(421.7±58.1) (283.42-606.8)	(8.0±1.1) (5.38-11.53)

Table 4.10: Comparison of patient exposure parameters and effective dose during PET/CT examination							
Author	CT Modality		Tube potential (kVp)	Tube current-time product (mAs)	CTDIvol (mGy)	DLP (mGy.cm)	Effective dose (mSv)
Current study	GE 64 Slices	20	120*	28 (3.0-60.0)	19.8 (28.2-8.3))	2002 (749.5-2826.8)	30.0 (8.2-42.4)
Khamwan et al, 2010. Thailand	CTI/Siemens 16-slices CT	35	120	75 to 173 112+21.68	-	-	10.04 to 21.98 (14.45+2.82)
Kaushik et al, 2013, India	16-slice PET/CT GE)	300	120	-	19	547	11.5
Quinn et al, 2016, USA	GE 16 Slices		120	39.0 ± 11.2 (27.4 to 69.4)	5.1±0.6	464 ± 86	5.3 ± 1.0

Table 4.11: Patient exposure parameters in PET/CT examinations.					
CT Modality	Tube potential (kVp)	Tube current-time product (mAs)	Volume CT dose index CTDIvol(mGy)	Dose length product (DLP) (mGy.cm)	Effective dose (mSv)
GE 64 Slices	120*	28 (3.0–60.0)	19.8 (28.2–8.3)	2002 (749.5–2826.8)	30.0 (8.2–42.4)

Table 4.12: Contribution of CT and PET effective dose with previous studies.					
Authors	Radiopharmaceutical	Effective Dose (PET) (mSv)	Effective Dose (CT) (mSv)	Effective Dose (PET/CT) (mSv)	%CT
Current Study	18F-FDG	8.0±1.1			
Adeleye and Chetty (2018)	18F-FDG	5.40	2.38 – 39.65	8.0 to 24.05	77
Quinn et al. 2016	18F-FDG	9.0 ± 1.6	5.0 ± 1.0	14 ± 1.3	
Mahmud et al. 2014	18F-FDG	6.30	7.50	21.46	29 – 71
Kaushik et al. 2013	18F-FDG	5.8	8.2 - 11.5	13.1	19 – 24
Khamwan et al. 2010	18F-FDG	4.40+0.61	14.45+2.82	18.85	23 -77
Huang et al. (Radiology 2009)	18F-FDG	6.2	7.2 -26.0	13.4 - 34.2	54- 76
Jadvar et al. (Sem NM 2007)	18F-FDG	7.4	1.5 – 9.0	8.9 – 16.4	17 – 55
Brix et al. (JMN 2005)	18F-FDG	5.7 – 7.0	16.7 – 19.4	22.4 – 26.4	74
Wu et al. (EJNMMI 2004)	18F-FDG	10.7	19.0	29.7	64

Table 4.13. Nuclear medicine equipment		
Equipment	No. of Equipment	Vendor/ Model
PET-CT Units	3	GE Discovery VCT PET/CT, (8, 64,64 CT slices)
SPECT CT	2	Symbia, Siemens , 6 & 16 CT slices
SPECT	5	2 Sybmia SPECT T6
		2 Philips SPECT
		1 Philips SPECT CardioMD IV

Table 4.14. characteristics of radio- isotopes used in nuclear medicine department			
Radio isotopes and radiopharmaceuticals	Half-life ($T_{1/2)}$	Decay mechanism	Energy range (keV)
^{18}F (^{18}F-NaF, FDG)	109.77 m	β^+	511
^{67}Ga	3.26 d	EC	93 -300
^{13}N	9.97 m	β^+	511
^{99m}Tc	6.01 h	IT	140
^{123}I	13.3 h	EC	159

Table 4.15. Occupational exposure in PET /CT units				
Gender	No	$H^{p}_{(10)}$ (mSv)	$Hp_{(0.07)}$ (mSv)	Extremity (mSv)
Male	3	0.65±0.24 (0.33-0.97)	0.65±0.29 (0.33-1.02)	2.52 (0.66-14.8)
Female	6	0.48±0.11 (0.22-0.80)	0.53±0.20 (0.24-0.82)	7.56 (0.78-11.53)
Overall	9	0.57±0.18 (0.22-0.97)	0.59±0.25 (0.24-1.02)	5.04 (0.14-11.53)

Table 4.16 Occupational exposure in SPECT/CT and SPECT units				
Gender	No	Hp(10) (mSv)	$Hp_{(0.07)}$ (mSv)	Extremity (mSv)
Male	12	0.19±0.06 (0.10-0.35)	0.19±0.06 (0.09-0.35)	4.49 (0.41-9.64)
Female	9	0.25±0.09 (0.11-0.47)	0.27±0.10 (0.13-0.50)	16.1 (2.07-25.13)
Overall	21	0.22±0.08 (0.10-0.47)	0.23±0.08 (0.09-0.50)	10.29 (0.41-25.13)

Table 17. Overall occupational exposure in nuclear medicine department (SPECT and PET systems)				
Gender	No.	$Hp_{(10)}$	$Hp_{(0.07)}$	Extremity
Male	15	0.64±0.34 (0.1-3.16)	0.63±0.35 (0.10-2.42)	10.59 (1.1-9.15)
Female	15	0.40±0.16 (0.1-1.84)	0.45±0.14 (0.10-1.88)	7.46 (0.73-25.01)
Overall	30	0.52±0.25 (0.1-3.16)	0.54±0.25 (0.1-2.42)	9.03 (0.73-25.01)

Table 4.18. Annual cumulative dose in the nuclear medicine department (in mSv)				
Gender	No	Hp(10) (mSv)	Hp(0.07) (mSv)	Extremity (mSv)
PET/CT	9	4.7±2.9 (0.4-9.1)	4.9±3.1 (0.5-9.9)	20.4 (0.4-118.8)
SPECT/CT & SPECT	21	1.4±1.3 (0.1-3.7)	1.4±1.3 (0.1-3.8)	36.1 (0.1-298.0)
Overall	30	3.05±2.1 (0.1-9.1)	3.15±2.2 (0.1-9.9)	28.25 (0.1-298.0)

Table 4.19. Comparison between current study of Hp(10) and prior literature values Nuclear medicine technology:		
Study	Country	Range of annual effective occupational dose (mSv)
UNSCEAR	UN	0.86 to 1.4
Wu et al, 2005	China	7.3
Al Haj and Lagarde, 2002	KSA	0.5 to 1.2
Mustafa et al, 1985	Kuwait	1.38– 6.58
Martins et al, 2007	Portugal	3.45
A. Al-Abdulsalam et al, 2013	Kuwait	3.70
McEwan et al, 1988	New Zealand	0.27 to 1.42
Kamenopoulou et Al, 2000	Greece	0.59 to 0.82
This study	KSA	1.4

Table 4.20. X- ray units			
X-ray Machine	Numbers	Max. High Voltage (kVp)	Max. Tube Current (mA)
Digital	14	150	500
Radiography C- arms	3	125	500
Mammography	5	40	560
Fluoroscopy	2	150	800
CT	9	150	700
Portable X-ray	20	141	560

Table 4.21. Annual occupational exposure for radiologist during two consecutive years		
Years	H_p (10) (mSv)	Hp (0.07) (mSv)
2017	4.5 ± 6.1 (0.1 - 14)	4.6 ± 5.9 (0.1 - 22.5)
2018	4.7 ± 7.8 (0.1-25.5)	5.6 ± 8.5 (0.1 - 25.5)
Average	4.6 ± 7.0 (0.1 - 25.5)	5.1 ± 7.3 (0.1 - 25.5)

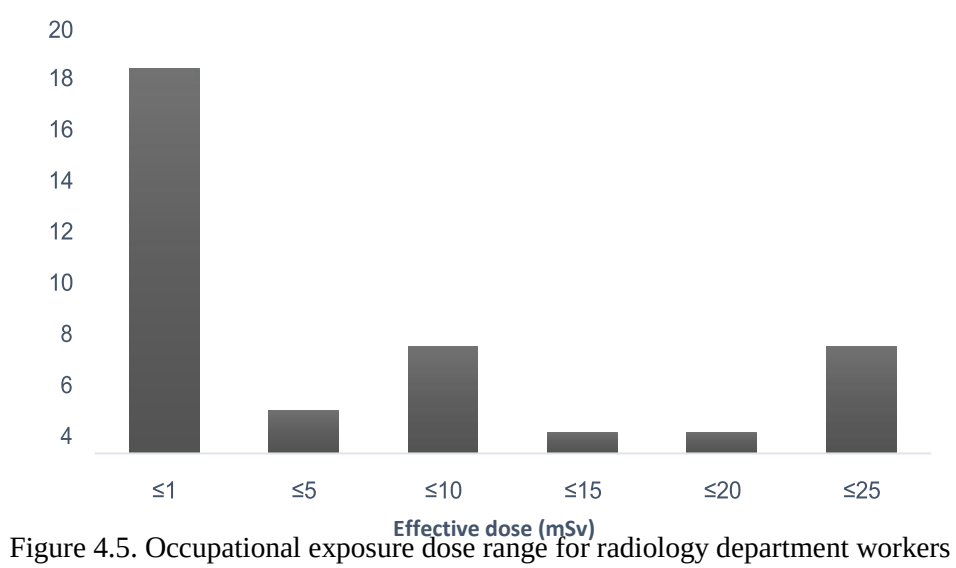

Figure 4.5. Occupational exposure dose range for radiology department workers

Table 4.22: Mean, ±Sd and range of patient demographic data and administrated activity in thyroid cancer by using Lutetium-177 (^{177}Lu)									
Gender	No. patient	Age	BMI	administered activity (MBq)	Effective Dose (mSv)	dose rate first day (mR/hr)			
						30 cm	100 cm	300 cm	behind bed shield
Male	20	(59.5±16.8) (27-87)	(23.59±4.35) (19.10-35.45)	(6972.7±977.2) (4329-7918)	(±) (-)	(8.85±2.56) (3.9-14)	(1.69±0.40) (0.8-2.30)	(0.11±0.069) (0.06-0.40)	(.091±0.022) (0.03-0.10)
Female	13	(59.8±6.8) (55-73)	(32.88±12.32) (18.58-40.46)	(7334.5±803.4) (4810-7955)	(±) (-)	(7.39±2.56) (3.2-12)	(1.51±0.21) (1.2-1.80)	(0.12±0.087) (0.04-0.40)	(0.096±0.027) (0.03-0.10)
Total	33	(59.6±13.7) (27-87)	(28.13±7.92) (18.58-40.46)	(7115.2±917.2) (4329-7955)	(±) (-)	(8.28±2.62) (3.2-14)	(1.62±0.34) (0.04-0.40)	(0.11±0.08) (0.04-0.40)	(0.089±0.024) (0.03-0.10)

Table 4.23: Mean, ±Sd and range of patient demographic data in thyroid cancer by using Iodine-131					
Gender	No. patient	Age (y)	Height (m)	Weight (kg)	BMI (kg/m^2)
Male	44	(44.3±14.9) (21-77)	(1.8±0.1) (1.56-1.89)	(94.1±16.3) (67.9-129.0)	(30.7±4.7) (22.0-40.7)
Female	138	(42.7±13.7) (16-81)	(1.7±0.1) (1.3-1.7)	(72.3±14.9) (33.7-112.6)	(29.5±5.9) (15.4-43.4)
Total	182	(43.5±14.3) (18.5-79)	(1.75±0.1) (1.4-1.78)	(83.2±15.6) (50.8-120.8)	(30.1±5.3) (15.4-43.4)

Table 4.24: Mean, ±Sd and range of patient demographic data in thyroid cancer by using Iodine-131										
Gender	administered activity (MBq)	Effective Dose (mSv)	dose rate first day (mR/hr)				dose rate first day (mR/hr)		dose rate first day (mR/hr)	
			30 cm	100 cm	300 cm	Behind bed shield	30 cm	100 cm	30 cm	100 cm
Male	(4503.0±2046.6) (1825.5-8066.0)	(25.7±11.7) (10.4-45.9)	(59.8±30.9) (15.0-138.0)	(11.4±5.6) (2.5-23)	(0.4±0.2) (0.01-1.3)	(0.4±0.2) (0.01-0.9)	(20.4±8.6) (6.5-38.0)	(5.6±2.8) (1.2-13.7)	(7.7±4.6) (0-18.0)	(1.5±0.6) (0-2.5)
Female	(3984.3±1996.2) (1512.2-8066.0)	(22.7±11.4) (8.6-45.9)	(49.9±31.1) (10.0-137.0)	(9.9±5.3) (2.5-24)	(0.4±0.2) (0.1-1.2)	(0.4±0.2) (0.03-1.2)	(16.5±8.2) (3.5-64.0)	(4.1±2.3) (1.1-15.0)	(5.1±3.3) (0.6-15.0)	(1.1±0.5) (0.1-3.0)
Total	(4243.7±2021.4) (1668.9-8066.0)	(24.2±11.6) (9.5-45.9)	(54.9±31.5) (12.5-137.5)	(10.7±5.5) (2.5-23.5)	(0.4±0.2) (0.05-1.2)	(0.4±0.2) (0.02-1.1)	(18.5±8.4) (5.0-51)	(4.9±2.6) (1.15-14.4)	(6.4±3.9) (0.3-16.5)	(1.3±0.55) (0.05-2.8)

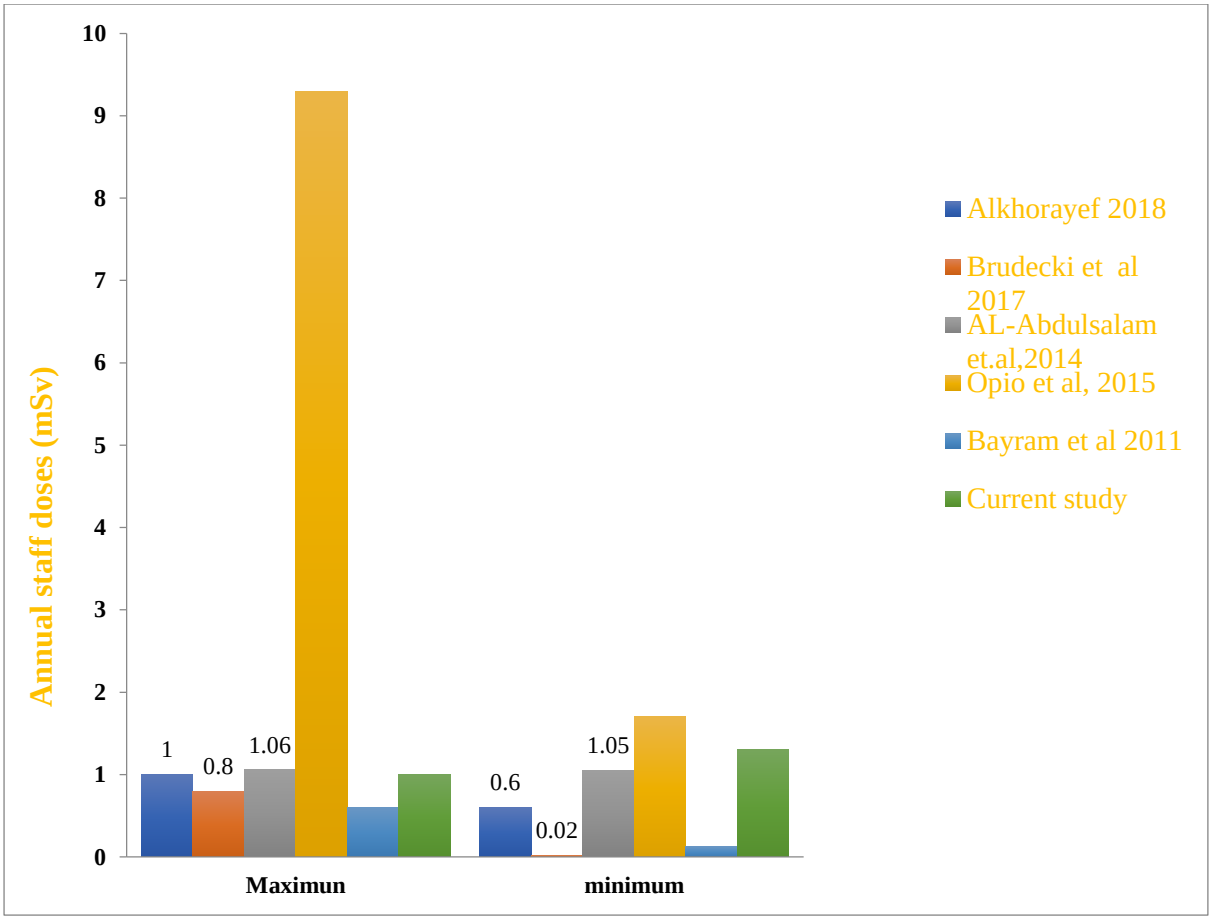

Figure 4.6. Occupational exposure compared with previous studies

Chapter Five

Discussion, Conclusion and Recommendations

5.1 Discussions:

Fluoro-D-glucose (18F-FDG) PET/CT and patient dose:

Patient radiation doses in PET/CT imaging depend on a number of factors affecting image acquisition. Of the 636 patients undergoing PET CT procedures in this study 41.4% (263) were female. Table 4.5 presents patients demographic data (age in years, weight (kg) and BMI (kg/m^2)) for lymphoma, nasopharyngeal carcinoma, thyroid and other PET/CT procedures. The BMI shows most patients were overweight and obese (the normal range of BMI is 18.5–24.9), the weight variation affecting administered activity and CT image acquisition parameters and hence the radiation dose. Tables 4.6-4.9 show the patient demographic data and image acquisition parameters used. The male and female effective doses were comparable, comparing favourably with a previous study that also showed no significant variation due to gender differences (Quinn et al., 2016). The mean and range of administered activity (AA) in MBq and effective dose (in mSv) respectively, were: for lymphoma 433.9 ± 70.6 (297.5-735.9) and 8.2 ± 1.3 (5.7-13.9); for nasopharyngeal carcinoma 417.7 ± 55.9 (325.6-547.6) and 7.9 ± 1.1 (6.2-10.4); for thyroid 450.1 ± 55.9 (344.1-566.1) and 8.6 ± 1.4 (6.5-10.8) and; for others procedures 421.6 ± 58.3 (283.4-606.8) and 8.0 ± 1.1 (5.4-11.5) (Table 1). The mean and range of tube current-time product (mAs) for CT procedure were 28 (3.0-60.0). A 120 kVp constant tube voltage was used for all patients. The mean dose length product (DLP (mGy.cm) and $CTDI_{vol}$ (mGy) are presented in Table 4.10. The mean effective dose is 30 mSv per CT procedure, illustrated that CT exposed the patients to higher dose compared to PET alone. Table 7 shows exposure setting for CT in PET/CT systems compared to previous studies (Quinn et al, 2016; Kaushik et al, 2013; Khamwan et al, 2010). All previous studies used fixed tube voltage (kVp) and wide range of

tube current time product (mAs) suggesting that exposure parameters not optimized. Table 4.12 shows patients' effective dose from use of the PET and CT imaging systems separately and also for the overall procedure, noting the latter to be greater than that reported in previous studies (Adeleye &Chetty 2018; Quinn et al. 2016; Mahmud et al. 2014; Kaushik et al. 2013; Khamwan et al. 2010; Huang et al.2009; Jadvar et al.2007; Brix et al. 2005; Wu et al. 2004). Effective dose (E) is the dose quantity of choice, providing relationship between radiogenic risk and radiation dose, involving tissue and organ sensitivities and also radiation quality for different ionising radiations, allowing meaningful comparison of the radiation dose from the radiopharmaceutical and the x-ray contribution to the PET/CT scan. Previous published studies show higher effective dose from CT compared to PET (Table 4.12). Huang et al.2009 reported that CT contributing up to 80.7% of patients total effective dose compared to effective dose resulting from PET alone (Huang et al., 2009). The higher doses in CT compared to PET is attributed to the greater tube current time product (mAs) and large scan area used for thicker body structures. In contrast, Quinn et al. (2016,) reported the converse, with PET contribution to the total effective dose per procedure of up to 75%, with 35% only for the CT procedure. This was attributed to the higher administered activity (454 (152-488) MBq reported, compared to the standard activity used in most previous studies (370 MBq). In addition, a higher pitch (1.78) and lower mAs contributed greatly in effective dose reduction in CT procedure.

The probability of radiation-induced cancer is 1.0 radiation-induced cancer per 500 PET/CT procedures. With the expanding role of PET/CT outside of oncological clinical indications and with availability of treatments that now result in improved patient survival rates, reduction of radiogenic risk is crucial. It has been observed herein that the technologists have tended to focus more on the patient risk from radiopharmaceuticals rather than CT radiation risk. Increased technologist awareness can result in patient' dose reduction. It has been

reported elsewhere that efficient use of current dose reduction measure in CT such as tube modulation may reduce the dose by up to 50% without affecting the quality of the image (Kalra et al., 2003). Further, the patient imaging protocol must be designed according to patient weight and

clinical indications rather than providing high image quality without justified clinical need or use of unnecessary scan length or exposure parameters.

4.7 Staff radiation dose and estimated risk in an interventional radiology department

Occupational exposures are influenced by various factors, including the type of procedure, dose-rate, exposure parameters (kVp and mAs), radiation field size, staff protection and skills as well as the annual workload (UNSCEAR, 2008). The measurements are presented in Table 4.21, the mean annual effective dose and range (in mSv) for Hp (10) and Hp (0.07) being 4.6 ± 7.0 (0.1–25.5) and 5.1 ± 7.3 (0.1–25.5), respectively. The results show five of the radiologists (16% of the total) receiving annual effective dose above the annual dose limits, while 14 workers (44% of the total) receiving radiation doses above 10.0 mSv per year. 56% of the staff received annual doses of less than 1.0 mSv per year (Fig. 4.9). The average dose equates with a probability of one incidence of cancer per 4000 radiology workers. During endoscopic retrograde cholangio-pancreatography (ERCP), Hysterosalpingography (HSG), cardiac catheterisation and urethrographic procedures, the radiologists need to be alongside the patients in order to perform the necessary manipulations. With complex fluoroscopy procedures, staff can be expected to spend more protracted durations with the patient, radiation dose being obviously greater if an over-couch X-ray tube is used or beam orientation is sub-optimal. Within the X-ray room, distant from the primary beam and patients, nurses provide assistance for less invasive procedures (receiving less intense

scattered radiation). In Riyadh, the practice for technologists is always to stand behind a leaded shield and as such their annual dose has been found to be less than 1.0 mSv.

Making comparison with previous published studies, Chida et al. (2013) reported that on average the physicians received a mean and standard deviation annual effective dose of 19.8 ± 12.5 mSv, greater than that found in current study (Table 4.20). Table 4.21 shows that technologists in radiology departments tend to receive the least dose while the physicians are exposed to more elevated doses. A lower value of effective dose was reported by Haga et al. (2017), at 10.0 ± 2.6 (3.0–15.6) mSv. Alkhorayef et al. (2020); Chinangwa et al. (2017), AlAbdulsalam and Brindhaban (2014) and Chida et al. (2013) reported radiographic technologist annual effective doses of below 4.0 m Sv, AlHaj et al. (2004) additionally reporting 80% of annual exposure doses to radiography technologists to be below the detection limits. As expected, radiologists are exposed to greater risk compared to technologists. Proper training is needed to ensure the avoidance of unnecessary exposure, as for instance in using last image hold and pulsed fluoroscopy capabilities. Additionally, previous research has shown aprons of 0.5 mm lead equivalent thickness to offer adequate dose reduction, up to 90% if the scattered radiation arises from the patient, while using 0.25 mm lead equivalent aprons are adequate for staff protection in NM departments (Meisinger et al., 2016; Deb et al., 2015).

4.8 Occupational and ambient radiation exposure from during targeted 177-Lu Therapy

Lutetium-177 is being increasingly used in theranostic applications for Targeted radionuclide therapy (TRT), resulting in marked progress in patient management with limited side effects (Kwekkeboom et al., 2008). Among the main advantages of the Lu-177 is that it is of suitable half-life and gamma energy, also available, facilitating diagnostic and therapeutic application.

Usually in TTR, the patient is treated over many treatment cycles while monitoring the progress by image acquisition from gamma rays. For this, several SPECT images can be collected at multiple time points to evaluate tumour uptake. Table 1 shows the mean Lu-177 administered activity (MBq) along with the patient cohort characteristics [age (in years), BMI (kg/m2) and measured dose-rate from the patient (noting that the Victoreen 451P gives readings in mR/hr, with 1 mR/h equivalent to 10 μSv/h)]. On average, with some 10% of the radiopharmaceutical being found to remain within the patient 24 hours post-administration, the dose rate to staff, other patients and family members is drastically reduced within a correspondingly relatively short time after injection. However, repetition of the procedure, typically at least 4 times, increases the hazards, being more restrictive for family members due to the limited public annual dose limit (1 mSv). Levart et al., 2019, reported mean dose-rates (in μSv/h) of 15.0 (5.0–25.0) at 1 m distance from the patient receiving therapy, comparable with that of present study, showing a mean dose rate (in μSv/h) at the same distance of 16.2 (8.0-23.0). Additionally, herein the dose rate (in μSv/h) at 0.3 m was 82.0 (32.0-140.0) while at 3 m the dose rate decreased to 1.1 (0.4-4.0) μSv/h, a distributed source not being expected to conform with the inverse-square law rule expected of a point source. With use of the bedside shield, the dose was found to drop below 0.1 μSv/h at 2 m distance (Table 4.22). The ambient dose in the corridor outside of the isolation room was found to be 1.2 mSv over 11 months while the ambient dose at the nursing station was below the detection limit for the particular dose rate. Here it is to be noted that the amount of activity used per treatment cycle at this Centre is 7.4 MBq, practiced as standard, sparing normal healthy critical organs and tissues (kidneys and bone morrow), providing tumour control at reduced side effect, also ensuring the whole body radiation dose remains within the safety limit. Kam et al. (2012) have reported accumulated doses of up to 23 Gy and 2 Gy for the kidneys and bone marrow respectively, radioprotective agents potentially being needed to

protect such organs at risk. With such treatment regimens, the survival rate has been reported to increase to more than 40 months due to an associated ability to increase the number of treatment cycles (Huizing rt al., 2018,Sandström et al., 2013). From the radiation protection viewpoint, a pure beta emitter would present no practical occupational risk. With a maximum tissue penetration of not more than 2 mm such a beta emitter would be useful for treatment of small lesions while at the same time sparing adjacent normal tissues. However, given the reality of de- excitation via gamma rays and the associated utility in diagnosis, the main source of occupational exposure results from this in combination with close contact with patients during administration, image acquisition and communication. In current study, to ensure minimal ambient dose, the patients, each kept in a separate room during treatment, were carefully checked prior to discharge in order to reduce the probability of contamination. The patients treated at this Centre are only released when the Lu-177 dose-rate at a separation of 1 m falls below 20 μSv/h. Even so, careful instructions for patients and family members are nevertheless required, with potential contact hours following each cycle of treatment cycles foreseably leading to a dose from the overall therapy that could exceed the annual dose limits for members of the public. Levart et al. (2019) estimated mean and range of partner doses (in mSv) from 177Lu-DOTATATE administrations of without restrictions per treatment cycle for 20 days are 6.2 (2.0–17.9) and 7.1 (2.4–20.0) for in-patients and out-patients respectively. Olmstead et al. (2015), reported a dose rate 20 hours after injection of 6.6 μSv/h, consistent with current study, suggesting restriction upon close contact with 177Lu-DOTATATE treated patients of between 3 to 15 days, additionally remaining off work for at least 5 days to ensure annual exposure to colleagues and members of the public not exceeding 1.0 mSv per year. Staff at this Centre are regularlly monitored using TLD dosimetry for all activities, including therapeutic radioiodine and PRRT. Annual doses (in mSv) of 9.0 ± 1.8 (6.0-11.0) have been found, radioiodine exposures contributing up to 85%

of the occupational exposure, with for the most part such patients staying longer in hospital, also receiving greater administered activity.

4.9 Occupational Exposure and radiobiological risk from thyroid treatment with radioiodine -131

The results of this study represent 182 (138 (75.8%) females and 44 (24.2%) males) patients' session occupational and ambient dose for one year for patients treated with radioiodine 131. Patients demographic data (age (y), weight (kg) and height (m)) showed that the majority of patients are overweight and obese with average BMI (kg/m^2) was 30.1±5.3 and ranged between 15.4 to 43.4. The mean and range of administered activity (AA, MBq)) and effective dose (mSv) were 4243.7±2021.4 (1668.9-8066.0) and 24.2±11.6 (9.5-45.9), respectively shown in table 4.23. The mean and range of AA (MBq) and effective dose (mSv) were 1507.9 ±324.1 (977.9-1836.9) and 8.6±1.8 (5.6-10.5) at the same order (Table 4.24). The annual occupational doses were 1.0 mSv. The ambient doses at isolation rooms after room cleaning and corridors is 1.0 mSv. Staff contamination with radioiodine is below the detection limit of the system. Table 4.24 shows the dose rate measurements at different distances over three days with and without shielding barrier. The mean and range of effective doses resulted from administered activity is 24.2±11.6 (9.5-45.9), which is very high and convey a risk to comforters during hospitalization.

Iodine-131 therapy is commonly used as an effective theranostic radiopharmaceuticals for thyroid disorders patients due to its ability in providing safe treatment from beta rays. Gamma emission is the main source of external exposure for nuclear medicine personnel. The process of high amount of radioactivity in radioiodine treatment activity ranging from 1668.9-8066.0 MBq per patient is administered. Thus the patients become an open source of radiation exposure to the all surrounding personnel and to the environment through body

fluids and excrete. Thus patients' dose is monitored daily to ensure the dose reduction according to the plan of the treatment. According to the hospital protocol the patients were released when the dose rate below 25 µSv /h at 1 distance to ensure that family members are well protected with certain guidelines. In the US, according to the regulation, the patients may release with radioactivity below 50 mSv per hour one meter distance. Although staff thyroid doses below the detection limit, Brudecki et al (2017) reported the measured activities ranged from 5.0 ± 2 Bq to 217 ± 56 Bq. The average occupational exposure (mSv) from this study is 2.1 (0.8-4.5) mSv per year while the ambient dose is 1.0 mSv per year. Figure 4.12 showed that the occupational doses is below the reported values in the literature. It is important to note that this occupational exposure include only the radiation doses resulted from working environment. All other source of other exposure are excluded such as background radiation, medical exposure as a patient and contribution as a volunteer in scientific research. Radiation induced cancer risk resulted from occupational exposure is far below the annual exposure (20 mSv/year). However other effects due to ionizing radiation were reported in the literature. For instance, Małgorzata et al., 2014 reported that ionizing radiation occupational exposure induce the DNA damage in leukocytes of nuclear medicine employees. While the ambient dose at different locations is less than 1.0 mSv per year, Abu-Khaled et al., 2009 reported higher for annual shallow and deep dose rates values at different locations including patient bed (226 and 175 mGy), bathroom (94 and 72 mGy) and visitor reception (12 and 10 mGy). Special guidlines regarding time and distance are recommended to ensure that the annual dose is below the limit .(Abu-Khaled et al., 2009).

4.6 Assessment of occupational exposure and radiation risks in nuclear medicine departments

Nuclear medicine technologist exposures to ionising radiation from the different sources may be appreciable, occurring during preparation and administration of the labelled radionuclides, as well as

imaging of patients, in each case staff spending a relatively long time (including up to some 2.5 h post-injection) in proximity to the source. Additionally, in the case of 18F-FDG PET/CT, patients may require 15 min of full rest prior to initiation of the procedure. At KFSH&RC, some 6000 SPECT and SPECT CT procedures and up to 4000 PET CT procedures are performed annually, the staff clearly working in a particularly high workload environment as perhaps expected of a national referral hospital. Table 3 shows the results of occupational exposure for technologists working with three PET/CT units. In terms of Hp(10) and Hp(0.07) and during the period of the survey the results show for the same PET/ CT group that male staff were receiving doses some 25% greater than that to female staff. Conversely, for extremity doses these were some 67% greater for females than males. Table 4 reports occupational exposures in SPECT/CT and SPECT investigations for 21 workers. Contrasting with PET/CT results, in the SPECT/CT & SPECT group the data show female staff were receiving Hp(10) and Hp(0.07) doses some 25% greater than males while as before extremity doses were greatest for female staff, being 72% greater than that for male staff. The outcome can be attributed to the workload per group, with in PET/CT only three male technologists working on all procedures contrasting with the otherwise 67% female staff. In SPECT CT, 57% of the staff were male, lower doses being expected compared to that for female staff. In the literature, Shi et al. (2016) assessed global gender variation and dose in best practice nuclear cardiology, with only minor variations reported. As such, in consideration of present results, careful assessment of working conditions and training of staff are recommended in seeking to reduce occupational exposure gender differences at the present study centre. Figs. 4.5 and 4.6 present the year 2018 summary results of Hp(10) and Hp(0.07) for each month, Tables 4.15 and 4.16 showing the monthly summary dose values and their uncertainties. In use of such penetrating photons, little difference might be expected between the more superficial dose and deep tissue dose, marginally greater values of Hp(0.07) over Hp(10) being observed. In this context, Takahashi et al. (2008) previously reported that in gamma ray exposures, Hp(10) and Hp(0.07) were found to be equal using electronic dosimeters in occupational exposure environments. Exposure to the 511 keV radiation of 18F-FDG point to the potential for greater occupational exposures compared to staff working with conventional procedures (99mTc). In the latter context, Mettler and Guiberteau (2012) observed that at the time of the study up to 90% of

nuclear medicine procedures were performed using 99mTc, with other radionuclides including 131I, 123I and 201Tl. Table 4.17 shows the monthly average of both groups in terms of Hp(10) and Hp(0.07) and extremities. Extremity doses presented in Table 4.18 (36.1 mSv) are seen to be 40% greater in SPECT and SPECT/CT (20.4 mSv) than in PET/CT, manual injection being used for all patients for the former while in PET/CT automatic injection is more typical in daily practice. The wide variation observed in extremity dose leads to the reasonable inference that ring dosimeters are infrequently used by operators, the maximum observed extremity dose (298 mSv) albeit remaining below the annual dose limit (500 mSv/year). In the literature, in regard to the handling of unshielded syringes containing 99mTc of activity 370 MBq for 5-min periods, Neil (1969) reported operator hand doses of 5 mSv. As such, the use of automatic injectors and reduction of handling time are clearly important factors in seeking to significantly reduce hand dose. In present work, the annual mean dose and range in mSv for nursing staff was found to be 0.22 ± 0.1 (0.1–0.4) and 0.28 ± 0.2 (0.1–0.5) for Hp(10) and Hp(0.07), respectively. The greatest dose to nursing staff resulted from patient specialty cardiac procedures, the staff spending greater durations with patients in such cardiac exercises, involving electro cardiogram (ECG) lead placements/removal and cannula removal. The occupational doses per month showed some variation, attributed in good part to variation in workload for staff members. No correspondence was noticed between occupational doses in PET/CT and SPECT/CT and SPECT groups. The annual occupational doses per the two groups are presented in Table 4.18. The mean annual occupational deep and superficial dose exposures (3.1 and 3.2 mSv respectively) are both well below the annual dose limit to workers of 20 mSv) while the maximum dose value observed in an individual of 9.1 mSv is less than 50% of the annual dose. These results indicate current practice to be safe, with no one surpassing the dose limit. Thus said, further protection measures are required in order to reduce the dose to as low as reasonably achievable (ALARA), further increases in workload being anticipated. Regarding occupational exposure studies at nuclear medicine departments, the current dose is comparable with most previous studies (Martins et al., 2007; Kamenopoulou et al., 2000; UNSCEAR, 2000; McEwan, 1988, Mustafa et al., 1985), even noting the greater workload of the present department (Table 4.19). Occupational exposure to nuclear medicine personnel depend on the department design, interaction with the patient after radionuclide

administration and the availability and utilization of suitable protections tools, control of administered activity, radionuclide uptake and waiting time between injection and image acquisition. Fig. 4. Occupational exposure in nuclear medicine departments, which shows that the occupational dose is slightly higher compared to published previous studies ((Alnaaimi et al., 2017; Piwowarska-Bilska et al., 2011; Thea et al., 2002; Benatar et al., 2000). The higher exposure in this study attributed to higher workload in this department with 10,000 procedures annually. However, the occupational exposure is far below the annual occupational dose limits (20 mSv) (Fig. 4.8). These studies showed that PET/CT personnel is well protected in the light of present workload. Costa et al. (2018) reported that 41.5% of occupational doses in PET/CT imaging were due to radiopharmaceutical injection and 51.1% of dose during patient setup and positioning, while Seierstad et al. (2007) reported that 60% of the technologist dose resulted from handling the radiopharmaceuticals and 40% from patient's interaction in PET/CT imaging. Extremity doses to nuclear medicine technologists clearly result from preparation and administration of radiopharmaceuticals, especially in the manipulation and injection of unsealed source beta emitters that potentially will give rise to high skin doses to the upper extremities. Thus, the use of automatic injectors can contribute significantly to occupational dose reduction efforts. Proper justification of the nuclear medicine procedures and precise optimisation of the procedure along of the use of protective measures and accessories will prevent the staff from avoidable radiation induced cancer risk and ensure prevention from tissue reaction risk.

5.2 Conclusions

The outcomes of this survey correlate with the outcome of published studies from other international surveys. Administrated activities and effective dose will be valuable in providing regulation to the professional and regulatory bodies on dose levels for numerous examinations and procedures including ionizing radiation. To develop the administration of patient's doses involving ionizing radiation, radiation exposure data must be documented and scientifically compared with the international literature. Patients are exposed to three times higher radiation dose from cardiac and bone scans based on the administered activity.

The receipt by patients of significant doses during PET/CT procedures depends on the clinical indications for procedures as well as the imaging protocol. CT doses of some 73% of the total patient dose have been found, optimisation of CT aquisition parameters being seen to be vital in reducing the dose to its minimal value. Patient doses observed herein have been found to be greater than that of previous studies. Staff awareness of CT dose reduction parameters ensuring patients receive minimal radiogenic risk is paramount. Protection of patients from uneccessary radiation and shielding of radiosensitive organs is recommended regardless of the clinical indication of the procedure.

Occupational doses were monitored for 30 nuclear medicine personnel over a one-year period at King Faisal Specialist Hospital and Research Center (KFSHRC) in Riyadh. With staff exposed to relatively high-energy gamma rays, closely similar mean annual dose and ranges were reported for Hp(10) (deep dose) and Hp(0.07) (skin dose). In all cases, the extremity dose was below the annual dose limits (500 mSv) and annual occupational doses were well below the annual dose limit (20 mSv). The survey revealed wide variation in dose among the personnel (both male and female) and as such careful assessment of working conditions is recommended in an effort to ensure occupational exposures remain below annual dose limits.

In this study, 16% of the radiology department personnel have received annual effective doses above the recommended annual limit of 20 mSv, with other personnel receiving very

low doses, albeit with wide dose variation. 56% of the staff received annual doses of less than 1.0 mSv per year. While herein occupational exposures for workers in a radiology department have been found to be generally low, notable have been the higher effective doses received in fluoroscopic assisted interventions. It is crucial to increase awareness of protective measures and to ensure current radiology department practice follows national and international standards. Rigorous investigation of the work circumstances are essential in mitigating against staff over-exposures, careful dose monitoring also being recommended with additional dosimeters (e.g for the eye lens) if needed.

The annual occupational doses at King Faisal Specialist Hospital and Research Center fall below the international dose limits from nuclear medicine activities, including in this the relatively recent use of 177Lu-DOTATATE administrations. The ambient doses at 177Lu-DOTATATE isolation room corridors is 1.2 mSv over 11 months while the ambient dose at the nursing station was below the detection limit. Due to the personalized therapy nature in use of 177Lu, careful individual dosimetry is needed in order to better inform regarding the potential impact on risk arising from the activity administered in PRRT. Patient isolation is necessary in order to ensure that family members and members of the public receive optimally low doses, certainly below that of the legislated limit.

The staff exposure was below (2.1 mSv) the annual dose limits (20.0 mSv) in the light of the current practice and workload. Occupational exposure is comparable or lower compared to previous published studies. Proper patient isolation is important factor in staff radiation dose reduction. Staff contamination with radioiodine is insignificant. Staff are working in safe environment since ambient doses within micrograsy range. No contamination was detected for all staff member due to radioactive iodine. The current practice is comply with the international guidelines and radiation safety recommendations.

5.3 Recommendations:

- Increase number of patients to get more accurate patients.
- More hospitals and centers to get base line of diagnostic reference level.
- Apply such excellent studies in Sudan.

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