Kaunas University of Technology

Faculty of Mathematics and Natural Sciences

Investigation of Finger Exposure of Nuclear Medicine Workers

Master's Final Degree Project

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Kaunas, 2022

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Summary

Worker monitoring is a necessity for any radiation protection program. The personnel in Nuclear medicine (NM) department receives low whole-body doses which is easily monitored with passive individual dosimeters positioned on the chest. However, these workers come in close contact with radionuclides during labelling, dispensing or injecting of the radiopharmaceuticals to the patients, thus they may get higher doses to the hands. The biggest challenge in extremities monitoring is to foresee which part of the hand is the most exposed. Usually, for assessment of the hand doses, TLD ring dosimeter is used. The recommendations on how and where to wear ring a dosimeter depends on national regulations. Moreover, different correction factors are used for assessment of fingertip doses. The extremities monitoring is extremely relevant issue for investigation, due to the increasing number of nuclear medicine procedures and request for ensuring radiation safety, as well as updating working protocols for protection of the health of the worker.

The aim of this thesis was to evaluate personal dose equivalent, $H_p(10)$ to NM staff and dose equivalent to their extremities, $H_p(0.07)$ during manipulation of ^{99m}Tc labelled radiopharmaceuticals and to assess relationship between these two values. This investigation was conducted in the Nuclear Medicine Department of the Hospital of Lithuanian University of Health Sciences (LSMU) Kauno Klinikos. The doses of the extremities were collected and evaluated for four technologists working in this department. Moreover, measurements were performed using a prosthetic hand, to simulate the actions of the technologist during preparation of the ^{99m}Tc labelled radiopharmaceuticals, measurements were done using TLDs. Also, whole body doses were considered.

It was found that the whole-body exposure is less when working in a ^{99m}Tc preparation laboratory, than in radiopharmaceuticals injection rooms. Moreover, the results have shown that the technologist with the shortest working experience collected higher (14.36 μSv) accumulated doses in comparison with his colleagues. Based on the estimated highest doses to the fingertips, recommendations were prepared, regarding place, where to wear a ring dosimeter. For 4th and 1st technologists, the recommendation was to wear ring dosimeter on a middle finger of the right hand (maximum doses – 6.37 mSv and 1.27 mSv, respectively). Performed experiment with artificial hand phantom indicated an index finger as the most exposed one; the difference between, maximum dose of the finger and dose obtained at the ring place is 15 times. This leads to the suggestion that hand exposure measurement should be performed in order to give advice, regarding the ring finger dosimeter placement.

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Santrauka

Darbuotojų apšvitos stebėjimas yra esminė bet kokios radiacinės saugos užtikrinimo dalis. Branduolinės medicinos darbuotojai, gauna mažas viso kūno dozes, kurių stebėseną lengva vykdyti, naudojant pasyvius individualius dozimetrus, nešiojant juos krūtinės regione. Darbuotojai, artimai kontaktuoja su radionuklidais, kai atlieka radiofarmacinių preparatų ženklinimą, dozavimą ir suleidimą, todėl jiems tenka didesnė rankų apšvita. Didžiausias iššūkis stebint rankoms tenkančią dozę – numatyti, kuri plaštakos dalis yra labiausiai apšvitinama. Dažniausiai, galūnių stebėjimui naudojamas TLD žiedinis dozimetras. Rekomendacijos, kaip ir kur dėvėti žiedą, priklauso nuo šalies įstatymų. Be to, norint įvertinti pirštų galiukų dozes, naudojami skirtingi korekcijos daugikliai. Nuolat didėjant branduolinės medicinos procedūrų skaičiui, galūnių dozių stebėjimo tema tampa vis aktualesnė, siekiant užtikrinti radiacinę saugą bei atnaujinti darbuotojo sveikatos apsaugos darbo protokolus.

Šio baigiamojo darbo tikslas – įvertinti ir nustatyti viso kūno apšvitos dozę, $H_{\mathrm{p}}(10)$, ir galūnių dozę $H_{\mathrm{p}}(0{,}07)$ BM (branduolinės medicinos) personalui manipuliuojant ^{99m}Tc radiofarmaciniais preparatais ir įvertinti ryšį tarp šių dviejų dydžių. Projektas atliktas Lietuvos sveikatos mokslų universiteto (LSMU) Kauno klinikų Radiologijos skyriuje. Galūnių apšvitos dozės išmatuotos ir įvertintos keturiems branduolinės medicinos technologams. Taip pat, buvo atlikti matavimai naudojant dirbtinę ranką, siekiant imituoti technologo veiksmus ruošiant ^{99m}Tc radiofarmacinius preparatus, tam buvo naudojami TLD dozimetrai. Viso kūno apšvitos dozė taip pat buvo įvertinta.

Tyrimo metu nustatyta, jog dirbant ^{99m}Tc paruošimo laboratorijoje, viso kūno apšvita yra mažesnė, nei radiofarmacinių preparatų injekcijų procedūriniuose kabinetuose. Be to, rezultatai rodo, kad trumpiausią darbinę patirtį turintis technologas, surenka didesnes (14,36 μSv) viso kūno apšvitos dozes, lyginant su kolegomis. Remiantis didžiausiomis pirštų galiukų surinktomis dozėmis, buvo pateiktos rekomendacijos, kur dėvėti žiedinį dozimetrą. 4 ir 1 technologams rekomenduojama nešioti žiedinį dozimetrą ant dešinės rankos vidurinio piršto (didžiausios dozės – atitinkamai 6,37 mSv ir 1,27 mSv). Atlikus eksperimentą su dirbtinės rankos fantomu, paaiškėjo, kad labiausiai apšvitinamas rodomasis pirštas, o skirtumas tarp didžiausios užregistruotos dozės ir ties smiliaus pagrindu, yra 15 kartų. Remiantis rezultatais, rekomenduojama atlikti galūnių stebėjimą bent vieną bent kartą, tam kad būtų galima teikti tikslias rekomendacijas, kur dėvėti TLD žiedinį dozimetrą.

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Abbreviations:

ALARA – As low as reasonably achievable;

CB – conduction band;

CT – computed tomography;

DNA – deoxyribonucleic acid;

EBM – electronic band model;

EURADOS – European Radiation Dosimetry Group;

ICRP – International Commission on Radiological Protection;

LAR – lifetime-attribute risk;

LNT – linear no-threshold;

ND – non dominant;

NM – nuclear medicine;

NDR – national dose registries;

OD – optical density;

ORAMED – Optimization of RAdiation Protection of Medical Staff;

OSLD – optically stimulated luminescent dosimeter;

PET – positron emission tomography;

SPECT – single photon emission computed tomography;

TL – thermoluminescence;

TLD – thermoluminescent dosimeter;

VB – valence band;

Introduction

Annual exposure doses for medical employees have declined over the previous several decades, although occupational doses for specific applications, have remained rather high. Nuclear medicine operates, while using radioactive sources for therapeutic and diagnostic purposes, thus particularly this medical field, raises concerns about radiation exposure, received by the medical staff, due to high radionuclide activities being required, moreover, the handling of radiopharmaceuticals in a close contact to the extremities.

The rising use of radioactive substances in diagnostic and therapeutic medicine is due to a combination of better health care and an aging population [1]. Thus, the need for occupational monitoring only increases, especially in radiology departments. Due to the increased number of the activities, the relevance of the radiation safety topic became very important, especially in extremity monitoring, where doses might even surpass the international and national limits. Such studies could help the optimization of radiation safety and work protocols.

According to the studies, several procedures still use minimal safety and dosimetric equipment, potentially resulting in an underestimating of medical exposures, thus radiation monitoring has become more common as people are more concerned about the health effects of radiation. The main purpose of radiation protection is to keep the harmful effects of exposure to a minimum. External and internal exposures (from inhaled radioactive elements) are both a risk for nuclear medicine personnel [2]. The linear, no-threshold (LNT) connection describes a rise in the likelihood of cancer development with the increase in radiation dose [3]. The risk of cancer is stochastic and is related to the quantity of exposure, thus it is significant to keep tracks of the occupational doses, and evaluate safety measures on a frequent basis to ensure that employees are meeting the standards, and receiving the lowest possible doses. The exposure doses mostly increase, with bad working habits and poor working conditions of employees. Identifying the area of the maximum skin dose is one of the most difficult aspects of TLD monitoring. The problem is that it is difficult to predict which portion of a hand will be the most exposed. Moreover, during a single treatment, the distribution of dosages over the hand may change.

The aim of this work is to evaluate personal dose equivalent, $H_p(10)$, to NM staff and dose equivalent to their extremities, $H_p(0.07)$, during manipulation of ^{99m}Tc labelled radiopharmaceuticals and to assess relationship between these two values.

The tasks:

1. To assess personal whole-body doses and doses to the hands of radiotechnologists manipulating radiopharmaceuticals.
2. To compare *in vitro* and *in vivo* doses to NM technologist’s hands.
3. To find out relationship between whole body doses and doses to the hands of NM staff.
4. To simulate the activities of the technologists that are manipulating radiopharmaceuticals, using a prosthetic hand and perform dose distribution measurements over the hand area, including palm and fingers.

1. Literature review

1.1. Nuclear medicine

Nuclear medicine (NM) is a field which is related to diagnostic as well as radiopharmaceutical therapy, used for treatment purposes. Health care providers have the ability to investigate and follow the molecular as well as physiological mechanisms within the body by delivering a radioactive tracer to the patients [4]. PET/CT (positron emission tomography/computed tomography) and SPECT/CT (single photon emission computed tomography/computed tomography) are becoming more popular, when talking about nuclear medicine imaging. These hybrid system techniques can be used to diagnose and stage a variety of neurologic, cardiovascular, and oncology-related disorders. To provide a functional image of the patient, these systems utilize photons from decay of a radionuclide. These processes produce a wide energy spectrum as well as a complex radiation environment. In a nuclear medicine department, this necessitates preventative precautions for employee radiation protection [5].

The implementation of nuclear technologies in medical field is advantageous when talking about treatment, but comes at the cost of ionizing radiation exposure. High radionuclide activity, ranging from a few tens to thousands of MBq, is required in this area [6]. Some procedures have the potential to cause hazardous radiation exposures. In NM the radiation is administered by radionuclides, that is chemically conjugated to a pharmaceutical. The ionizing exposure to nuclear medicine personnel has always been a major problem in NM. The staff receives low whole-body doses that may be monitored with passive personal dosimeters worn/placed on the chest [7]. Nonetheless, the hand skin of the workers in NM is an organ the most at danger of excessive exposure when manipulating and administrating unsealed radiopharmaceuticals in routinely procedures. Personnel is exposed to ionizing radiation when they unpack, store, dispose of, and measure the activity of radiation sources, as well as when they prepare and administer radiopharmaceuticals. During and after diagnostic or treatment procedures, patients, injected with radioactive substances, also, become another source of radiation to the staff [8].

The majority of radiopharmaceuticals, usually, are manually labelled. The radiopharmaceutical labelling necessitates the usage of radionuclides with a number of diverse activities. Furthermore, the total daily activity of the isotope, handled by the staff is very high in some nuclear medicine departments, for example ^{99m}Tc isotope activity depends from a radiopharmaceutical and ranges in quantities from 50 to 150 GBq, and sometimes even up to 200 GBq [9].

For employees working with radiation, the ICRP (International Commission on Radiological Protection) proposes a dosage limit of 20 mSv per year, averaged over a period of 5 years. The ALARA (As Low As Reasonably Achievable) concept includes the reduction of exposure to individuals and to society to a minimum, evaluating economic and social factors, according to the ICRP standards. ORAMED (Optimization of RAdiation Protection of Medical Staff) was a large European initiative that established dose monitoring systems and proposed solutions for lowering staff exposure in nuclear medicine, cardiology and radiology departments. According to the findings of the ORAMED, around 20 % of workers may receive higher doses to the hands and skin than the permissible dose limit [7]. Given the reported trends in radiology and clinical experience around the world has shown that, regularly, staff dosage limits are not to be surpassed in departments, which use automated dispensing systems. Skin dosages to operating employees using semi-automated, as well as manual dispensing equipment, on the other hand, may be much greater and even exceed the annual recommended limitations [9]. Other areas of the body, including trunk and head, are normally protected from the radiation by use of various shields, in e.g. lead-based walls or lead-glass windows or radiation protection garments. Due to the efficiency of these guards, the dose rate incident on the covered parts of the body, including the eye lenses, can be reduced by a factor up to 10^8, making the exposure as minimal as possible [8]. Radiation protection is applied to secure humans from the impacts of ionizing radiation. It is ensured by three essential concepts – justification of the actions, optimization, and limitation of the dosages [10].

The equivalent dose to the hand skin is an estimation of the equivalent dose to the extremities in general. Regarding, the near proximity, between the hands and the source, as well as the diversity of radiopharmaceuticals, measuring maximal skin dose accurately in nuclear medicine is difficult [7]. In diagnostic NM, most of the time radiopharmaceutical is administered intravenously, but in some cases, it can be delivered orally, in food/drink, as well as inhaled as a gas. Radiopharmaceuticals can be absorbed or concentrated in an organ of interest or a tissue, which later is detected using an external camera that forms an image [11].

1.2. **Radiopharmaceuticals**

Nuclear medicine is based on use of radiopharmaceuticals for therapy and imaging. The needed functions and the choice of a radionuclide must be considered when designing and administering a radiopharmaceutical with precise localization qualities. The physical properties of the radioisotope determine, which element is suited for nuclear imaging [12]. A radiopharmaceutical, in general, is made up of three main parts: a vector molecule, a radionuclide, and a linker in the middle (Figure 1). The radioactive component is provided by the radioisotope, whereas the vector molecule targets biomolecules expressed in cells as well as tissues [13]. Moreover, when designing radiotracers, glucose metabolism is a significant subject to consider. Glucose homeostasis is vital in many aspects of life, and its disruption is linked to a number of serious disorders, including cancer. The unusual glucose metabolic phenomena, recognized as the Warburg effect, is identified as a hallmark of oncological diseases and is a prospective target for tumour imaging [14].

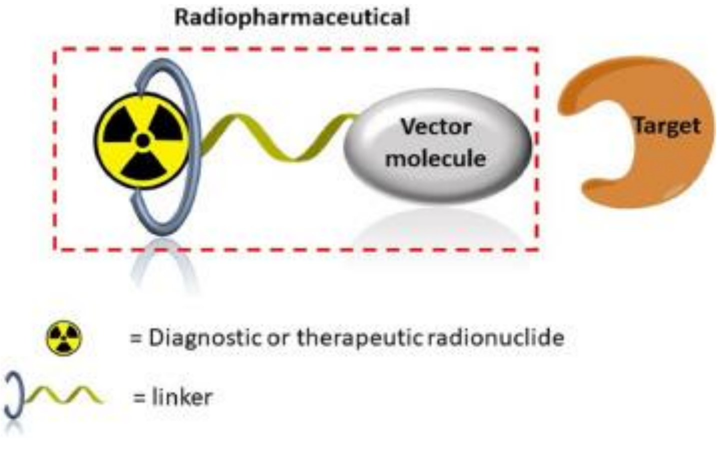


Fig. 1. Radiopharmaceutical shown in a graphic design [13]

Radiopharmaceuticals are composed of radionuclides with short, medium half-lifes, as well as a variety of physical features and biochemical pathways influence their clinical trial suitability. Diagnostic imaging agents with shorter half-lifes and attractive features for imaging (e.g., ^{99m}Tc for positron emission tomography) are normally created to characterize the physiological processes, to be present in specified disease states. To deliver radiotherapy as part of oncological treatment regimens, medium half-life radiopharmaceuticals with optimal qualities for therapy (e.g., ^{89}Sr, ^{90}Y, and ^{131}I) are produced [12]. The half-life of a radionuclide should be consistent with the duration period of the plasma vector, so that enough activity is presented in the body when an ideal signal/noise ratio is established. Small chemical compounds have a plasma half-life time of a few minutes, while peptides and antibody fragments have a plasma half-life time of hours, days, or even weeks. When a longer duration is needed to attain appropriate target tissue-to-background ratios, longer-lived radioisotopes should be used [13].

^{99m}Tc is widely used in diagnostics because of the short physical half-life time (6 hours) which means the shorter exposure of the patient. Moreover, it has monochromatic gamma ray emission (an energy of 140 keV), which is optimum for NaI (Tl) imaging with a gamma camera, SPECT and SPECT/CT. It also, possesses numerous oxidation states, allowing it to mark a wide range of compounds, and it is easily available and obtainable in nuclear medicine departments (NMDs) using a ^{99Mo}/^{99m}Tc generator [15]. ^{99m}Tc is used for over 80 % of all tests in nuclear imaging and 90 % of them used for clinical diagnosis. In 2008, the overall amount of treatments performed using ^{99m}Tc around the world was projected to be around 25 to 30 million per year, with 6 – 7 million going on Europe [16]. On the other hand, it is written that above 30 – 40 mln tests are done every year using ^{99m}Tc [17]. It is reported that the doses for pure 5 ml syringe which is held by fingers, collected from ^{99m}Tc are 8, 89 and 30 times lower than ^{18}F, ^{68}Ga and ^{124}I, respectively. Presumably, the higher skin doses are usually collected when working with beta emitters in comparison with ^{99m}Tc [18].

Therapeutic radiopharmaceuticals produced for imaging must have certain characteristics: 1) the decay of a radionuclide should be in certain energy emission ranges as well as in sufficient range for tomography detection; 2) the half-life time of a radionuclide indeed should be limited to a few hours; 3) the substances should never be contaminated by other radionuclides and other unnecessary particles; 4) isotopes should have specific activity; 5) the radiopharmaceutical needs to be free of toxicity [19, 20].

1.3. Lifetime risk

High dosage (> 100 mSv) impact on people and its evaluation methodologies are well established, due to evidence of ionization having a biological harm. Stochastic effects are unintentional and have a probabilistic aspect that is related to the exposure. Low dosage effects (< 10 mSv) without clinical symptoms in exposed individuals, and with a substantially limited detection capability for blood abnormalities, under the barrier dose of 500 mSv are known as stochastic effects. As a result, there is a lot of discussion among experts over whether small exposure doses have any effect on human health. However, everyone agrees that there is a risk of radiation-induced cancer, even from lower exposure doses [21]. Radiation safety evaluation is essential to ensure that activities meet the requirements and that recommended dosage limits are not exceeded, as stochastic risk increases with an exposure (especially higher risk of cancer) [22]. Organ dose for the lifetime is representing the amount of an annual organ dose sums obtained from collected monitoring information when the worker was exposed to radiation, potentially. The types of ionizing sources used, the radiation quality which was emitted by the radionuclides, and the interactions between the operator and the radioactivity all have a role for the organ doses. Other factors that determine tissue exposure include dispersed radiation effects, defensive shielding effects, and the gender of the person as well as physical morphology [23].

Medium or high exposures of ionizing radiation are said to cause temporary and permanent genotoxic and biological consequences, even the low doses increase the risk of a chromosomal damage. Due to the appropriate use of radiation shielding, the acute effects rarely happen, nevertheless, the long-term consequences associated with flow-doses are the main problem [24]. In a somatic cell, in an individual exposed to radiation, after non-lethal transformation, following the latency period, cancer might be developed [25]. Despite this, there is still a lot of dispute about the biological consequences of low-dose exposure (less than 100 mSv) [26]. The most sensitive organ to radiation is said to be the lens of the eye. The opacification can be present even at very low doses such as 0.5 mSv [27]. Staff working in nuclear medicine may be exposed to low-levels of radiation over extended time period and experience health consequences as a result [26]. In literature [22], the side effects of occupational exposure are reported, as eye-lens cataracts, left-side brain cancer, other non-malignant diseases and reversible white blood cells damage in the DNA (deoxyribonucleic acid), amongst nuclear medicine staff working with radiopharmaceuticals. Moreover, the higher risk of squamous cell carcinoma is reported in the literature [28]. Current models suggest that stochastic consequences can arise from a one single damaged cell. As a result, these effects have no dose threshold, and their severity does not always increase with a dose. The most serious danger posed by low-dose radiation is the development of oncological diseases. The ICRP has chosen a linear risk factor of 4.1 % Sv^{-1} for oncological diseases of adult workers, intended for radiation protection [29].

1.4. **Dosimetry parameters and dose constraints**

The effective dose is referring to eventual stochastic effects of the whole body, whilst the equivalent dose refers to a particular organ exposure (skin, extremities as well as the lens of the eye) [30]. The 2013/59 European Directive established dosage limits for the skin of the extremities, based on the guidelines of the International Commission on Radiological Protection (ICRP) which has set the limit of the 500 mSv equivalent dose per year. This skin limit, refers to an average dose per 1 cm^2 of mostly irradiated area [7]. In a reality, complying with the limit of 500 mSv/year for skin is troublesome, due to the need of monitoring of the most exposed area. This location is not known ahead of time, and it varies in each treatment, routinely, it is not the palm, but the tips of the fingers [18].

Absorbed dose *(D)* refers to the energy that is absorbed by a unit of mass of ionization and could be calculated using the following formula:

$$D = \frac{d\bar{\varepsilon}}{dm} \ , \tag{1}$$

where: $d\bar{\varepsilon}$ is the average energy transmitted in volume to the material, through ionizing radiation, *dm* refers to the substance mass in the volumetric element. The absorbed dose explains an average dose collected by the organs or tissue. The measurement unit for the absorbed dose is the Gray (Gy) [31].

The sum of equivalent doses which consists of external and internal exposures of all bodily tissues and organs, compounded by weighting variables, is known as the effective dose *(E)*:

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R} \ , \tag{2}$$

where: $D_{T,R}$ represents mean absorbed dose to organ/tissue *T* on account of radiation *R*, also *wR* represents the weighted factor (of ionizing radiation), *wT* is the weighted respective tissue or multiplier *T* of the organ [31].

Cumulative effective dose *(E (τ))* represents the sum of all the equivalent doses H_T *(τ)* which are accumulated in an organ or tissue because of the radionuclides introducing into the body, and is calculated by multiplying every dose with the right tissue weighting factor w_T according to the formula:

$$E(\tau) = \sum_T w_T H_T(\tau) \text{ [31]}, \tag{3}$$

The ICRP defined the protective values, which are: equivalent dose for the lenses – H_{eye}, and for the skin – H_{skin}, and the effective dose – E, determination of the exposure to the body. These operational numbers allow to determine the worth of the protection amounts in most of the circumstances. The quantity of the monitoring is called personal dose equivalent and is expressed as $H_{\text{p}}(d)$ [32]. The International Commission on Radiological Protection (ICRP) approved the "Statement on Tissue Reactions" in April of 2011, based on epidemiological data of radiation-induced cataracts at dose levels lower than those, previously considered threshold, and recommended a 20 mSv/year equivalent dose limit, which is set for the lens of the eye, averaging 5 years span, not a single calendar year exceeding more than 50 mSv (Table 1). This revised limit for the lenses of the eyes was a significant adjustment from the earlier dosage limit of the 150 mSv/year that was established by European standards in 2013 [33].

Table 1. Annual dose limits [34]

	Occupational exposure	**Exposure to students (16 - 18 years)**	**Public exposure**
Whole body effective dose (mSv)	20, averaged over five consecutive years 50 in a single year	6	1, averaged over five consecutive years in a single year
Eye lens equivalent dose (mSv)	150	50	15
Equivalent dose for the extremities (mSv)	500	150	50

The $H_{\text{p}}(10)$ is the whole-body dose obtained at a 10 mm depth from the surface of the skin (deep dose). $H_{\text{p}}(10)$ is used to calculate an effective dosage estimate, that eliminates both underestimation and overestimation. The dose obtained at a depth of 0.07 mm, represents the skin dose and is expressed as $H_{\text{p}}(0.07)$ (tissue depth which is equivalent to 0.07 mm) and is used to measure both skin and extremities. The sensitive human cells in the skin are usually between 0.05 mm and 0.1 mm, underneath surface of the skin, thus $H_{\text{p}}(0.07)$ is used for equivalent dose estimation. When monitoring the lenses, a depth of 3 mm is advised ($d = 3$), and $H_{\text{p}}(3)$ is used to provide an estimation of equivalent dose to the eyes. In practice, the measuring of $H_{\text{p}}(3)$ has been not commonly implemented for repetitive individual monitoring [30, 35].

Equivalent dose *(H_T)* represents the dose of the organ that is absorbed and multiplied by the weighted factor, that is depending on the radiation and its energy type, in accord to the following expression:

$$H_{T,R} = w_R D_{T,R} \tag{4}$$

where: $D_{T,R}$ – represents mean absorbed dosage in the organ or a tissue (T) because of ionization R, where w_R – respresents weighted factor of the radiation [31].

Cumulative equivalent dose *(H_T (τ))* is an integral value of dose rate equivalent that a person will receive over time (in a tissue or an organ), when radionuclides enter the body, and is calculated according to a formula:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} H_T(\tau)\, dt\,, \tag{5}$$

where: radionuclides enter the body at certain time t_0, where H_T *(t)* means the corresponding equivalent dose rate (for organ or tissue *(T)*) at a certain time *t*, and with the integration period τ [31].

Mean organ dose *(D_T)* in a specific organ or tissue *T* in the human body and can be expressed by the formula:

$$D_T = \frac{E_T}{m_T}, \tag{6}$$

where: the total energy that is deposited by radiation to an organ is E_T and mass of an organ is expressed as m_T [34].

1.5. **Dosimeters**

Dosimeter is a device or equipment used to analyse and measure the quantities of exposure such as absorbed and equivalent doses, kerma, and dose rate, either directly or indirectly. Dosimeter, together with a reader, are called a dosimetry system [36]. Due to the usage of protective apparel, two $H_\mathrm{p}(10)$ dosimeters, one under and one over the apron, are recommended, to provide a reasonable assessment of the effective dosage. More dosimeters for whole-body dosimetry which would include the extremities and lenses may also be essential in some circumstances. Due to the difficulty of wearing many dosimeters, they are frequently misplaced or worn inappropriately [32]. Ring and wrist dosimeters, which are calibrated in terms of absorbed dose, are commonly used for extremity monitoring $H_\mathrm{p}(0.07)$. As a result, dosimetry measurements should have the ability to assess the dosage in the most heavily exposed area or, at the very slightest, minimize undervalues. However, viable monitoring places are limited to the bottom of the finger or the wrist for practical reasons. Regarding the inhomogeneous dosage deposition upon that active layer of a dosimeter, the functional thickness is a highly significant point. Furthermore, the response of the detector changes greatly, depending on the radionuclide. Even if the dosimeter is as thin as possible and calibrated correctly, the spacing between both the source and the detector, could result in a further underestimation, regarding dosage deposition inside the material [37].

TLDs (thermoluminescent dosimeters), pocket or electronic dosimeters, OSLDs (optically stimulated luminescence dosimeters) are all examples of the external whole-body monitoring systems. The use of ring and wrist dosimeters with film or TLDs is one of the hand monitoring techniques. Some advanced electronic detectors can bring up a display readout of both the cumulative dose and dose rate, as well as an audible warning sound to warn the person if the radiation levels exceed a pre-set threshold [29].

1.5.1. Thermoluminescent dosimetry

For the estimation of $H_p(10)$ and $H_p(0.07)$ personal dosimeters or dosimetry systems are equipped to measure these occupational quantities. TLDs, OSLDs, and film badges are the most common current options for monitoring of absorbed dose [38]. Personal dosimeters are used to determine whether an occupational radiation dose is within safe limits. In occupational exposure, the use of the TLD is critical for establishing if the dosage received is below required tolerances as defined by regulations for radiological protection. TLDs have been used to measure gamma dosage in both outdoor and indoor contexts since they are sensitive and affordable [3]. The operation of TLDs are based on phosphorescence, which is accelerated with a suitable excitation by the form of heat, the material absorbs ionizing radiation, which is later released as an energy in some sort of light form, and the process is called luminescence [37]. The significance of thermoluminescence in dosimetry comes from the certainty, that such intensity of light (luminescence) emitted is precisely equal to an absorbed dose by an irradiated medium, necessitating sensitive detection and precise measurements of radiation exposure. The absorbed dosage is proportional to the emitted intensity of a light by a solid under favourable conditions, and so the administered dose in the radiation field can be evaluated using an appropriate calibration. The electronic band model (EBM) of a semiconductor (Fig. 2) can be used to establish one of the probable processes for TL (thermoluminescence) emission, with three key elements (e.g. mobile carriers (MC), charge carriers (CC), and recombination centres (RC), or traps (T)) as existent ones. Ionizing radiation can provide the energy needed to create mobile carriers which are usually called electrons and holes. While electrons are allowed to migrate from a VB (valence band) to the CD (conduction band), holes stay inside the valence band as well as they are free to roam near the VB. The mobile carriers become released at various temperatures, because of the light emission process, which entails the release of certain traps at diverse energies, arising in a glow curve, which is particular of the material having one or a few peaks [39].

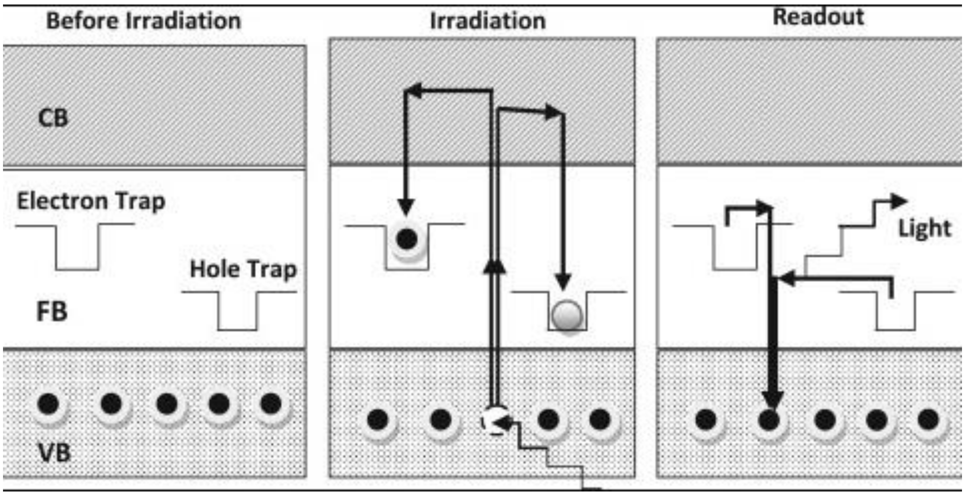


Fig. 2. The principle of thermoluminance phenomenon [39]

Today, numerous classes of materials which characteristics are examined in relation to the TL dosimetry criteria can be distinguished. Alkali, as well as alkali-earth haloids, in e.g. LiF and CaF_2, are typical examples of these materials. Sulphates (e.g. $MgSO_4$; $CaSO_4$) or oxides (e.g. Al_2O_3; BeO; SiO_2) are next on the list [40].

TLDs are indirect dosimeters with great sensitivity, homogeneity, minimal fading, accuracy, precision, energy dependence, and high reproducibility. The sensitivity of the TL material is known for detecting even very low doses [42]. Other advantages of the TLDs are various form availability, not expensive price and tissue equivalence. Minuses include, probability of losing reading, no instant readout, lost signal and the process of reading itself, is time consuming [36]. Although, TLDs are the most common dosimeter, as evidenced by their, other types of dosimeters for extremities monitoring are also available. Optically stimulated detectors, for example, are used on a regular basis, whereas active dosimeters are typically designated for study or optimization [17].

TLD-100 is a commercially available lithium fluoride doped together with Mg and Ti and is widely used radiation dosimeter not only in medical, but also in environmental dosimetry. It has gained popularity due to a number of characteristics listed above. In a range from 10 µGy - 10 Gy lithium fluoride shows a linear response. $Li_2B_4O_7$ (lithium borate) has a larger and more uniform energy reaction to the photons than LiF, though to thermal neutrons it is additionaly sensitive. Either LiF and $Li_2B_4O_7$ are tissue equivalents and are employed in dosimetry without the need for a complicated filter [42]. Lithium Fluoride is an alkali halide commonly used in personal dosimeters such as TLD-100 and TLD-100H. Powders, cylindrical and cubical chips, rods, and other kinds of TL dosimeters are applied. TLD-100 chips are made up of LiF crystals that have been doped with titanium as well as magnesium for increased number of traps together with luminescence centres [43].

1.5.2. GafChromic® films

When opposed to other 2D radiation detectors, radiochromic films are dosimetry media with desirable features. In radiation protection, radiotherapy as well as diagnostic radiology, films have been used in a variety of ways. They can be used as dosimeters for both quality and quantity dosimetry, and also as a display device, as well as an archival material [44]. They have all of the benefits of silver halide (also known as silver salt) films (2D dosimetry, slimness, ruggedness, permanency of the record), but none of the minuses, such as the need for non-tissue equivalence, impact on readout, sensitivity to visible light. Radiochromic films, make a radiation-induced picture, by a self-developed process, after the irradiation, and is driven by polymerization of a monomers of the diacetylene dye, having a great resolution. A radiochromic film is made out of a radiosensitive gel layer in between protective sheets. The radiochromic film is well suited for dose distribution assessment in medical and scientific radiation fields, with strong dose gradients due to its high resolution, modest response, that is dependent on the energy, as well as it being, almost tissue equivalent [45].

Dosimetry, using GafChromic^{TM} film is based on charged particles, which deposit their energy through a layer that is sensitive, and polymerization is initiated of a sensitive component. The piece of the irradiated film changes its colour because of the created polymers and the change in absorbance can be measured by a spectrophotometer. Based on the materials used, the colour change might be quite various. The intensity of darkening is dependent on the dose administered to the gel, and visible light has no impact. Most radiochromic film dosimeters, on the other hand, use materials that turn blue when subjected to radiation [46], [47]. Radiochromic films are often used for relative dosimetry and reference dosimetry measurements, and is considered a very useful tool for these kind of measurements [48]. EBT3 gafchromic films were introduced back in 2011 as a substitute for EBT2. A 28 µm active dosimetric layer is located between the two matte-polyester 125 µm substrate layers in these third-generation films. Despite the fact that the active layer content stays the same, EBT3 films have various advantages over EBT2 films, including interference pattern avoidance and a uniform structure [49, 50].

1.6. Investigation of the extremity doses

In Lithuania, research was conducted over the previous 26 years (1992–2017) to analyse the doses to the hands and thyroid – in order to identify the risk of getting cancer and other specific disorders for workers exposed to radiation. These organs are primarily affected when nuclear medicine operations using radioisotopes are performed [21]. Hand/finger exposure also contributes to the development of diseases, especially cancer. Despite the knowledge of possible stochastic effects, the dangers of long-term radiation are still unknown [51].

The information was gathered from five biggest hospitals of Lithuania, which included 272 distinct employment roles divided into four categories: physicians, technical and support employees, and others (technicians, engineers, physicists). The job length ranged from three to twenty-six years, with an average of ten years. Different techniques were used to measure doses, including scintigraphy (^{99m}Tc) and PET/CT exams which use ^{18}F-FDG. ^{99m}Tc is the most frequently utilized radiopharmaceutical in Lithuania, for different kinds of procedures, which are listed in the table below [21]. Gamma radiation is emitted by technetium with an energy of 140 keV [52], as mentioned above. As a result, personnel's hands can be exposed to substantial ionizing radiation equivalent doses, resulting in a need of additional monitoring and investigation, which was done during this research.

Table 2. Radiopharmaceuticals used the most in Lithuania [21].

Radiopharmaceutical	Procedure
^{99m}Tc-MAG3	Renal scintigraphy
^{99m}Tc-DTPA	Renal scintigraphy
^{99m}Tc-MIBI	Parathyroid investigation
^{99m}Tc-MIBI MP	Myocardial perfusion
^{99m}TcO4	Thyroid examination
^{99m}Tc-MAA	Lung perfusion

The use of ^{18}F-FDG for tumour scanning was initiated with the introduction of two new PET/CT systems in 2012, as well as 2014. Hand exposure doses were assessed every three months, and fingers were monitored upon a request. Doses were measured while wearing a safety apron, which was taken into the account. The lifetime-attributable risk (LAR) describes the likelihood of acquiring or dying from cancer, which results from ionizing radiation. In the same department, the highest average annual exposures were 15.8 mSv for a radiology technician and 10.9 mSv for a radiology nurse. Due to the malfunctioning ^{99m}Tc generator in 1994, such high dosages were estimated. Calibrated TLD chips were packed into the plastic bags and then fastened to the palms of the hands to estimate the dose (Fig. 2). The average exposure to the fingertips seems to be more than twice higher than the amount to the hands, according to the study [21], due to the fingertips being nearer to the radioactive substances in most instances, when handling radioactivity [18]. The evaluated probable risk for developing a thyroid cancer is almost six times greater for female employees (5.7) than male after evaluating the formation of thyroid and leukaemia cancer, although the risk is minimal when compared to life time spontaneous risk [21].

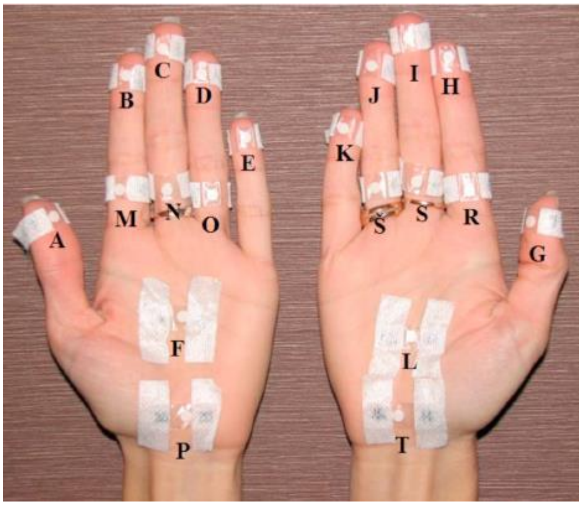


Fig. 3. Positioning of TLDs, for extremity monitoring in Lithuania [21]

As it was shown [53], TLDs were used to measure $H_p(0.07)$ for hands and fingers in five different nuclear medicine departments. 13 right-handed technologists participated in the research, the measurements were performed during routine procedures, which include generator elution, activity measurement, labelling and dispensing. TLDs were attached to the hand at 19 different positions (Fig. 4). It was found that the values for the fingertips are on average five times higher in comparison with values obtained from a ring dosimeter. Nevertheless, doses obtained by a wrist dosimeter were 25 times lower on average than doses received by the fingertips. This led to the conclusion that, the wrist dosimeters can only be used when applying correction factors [53].

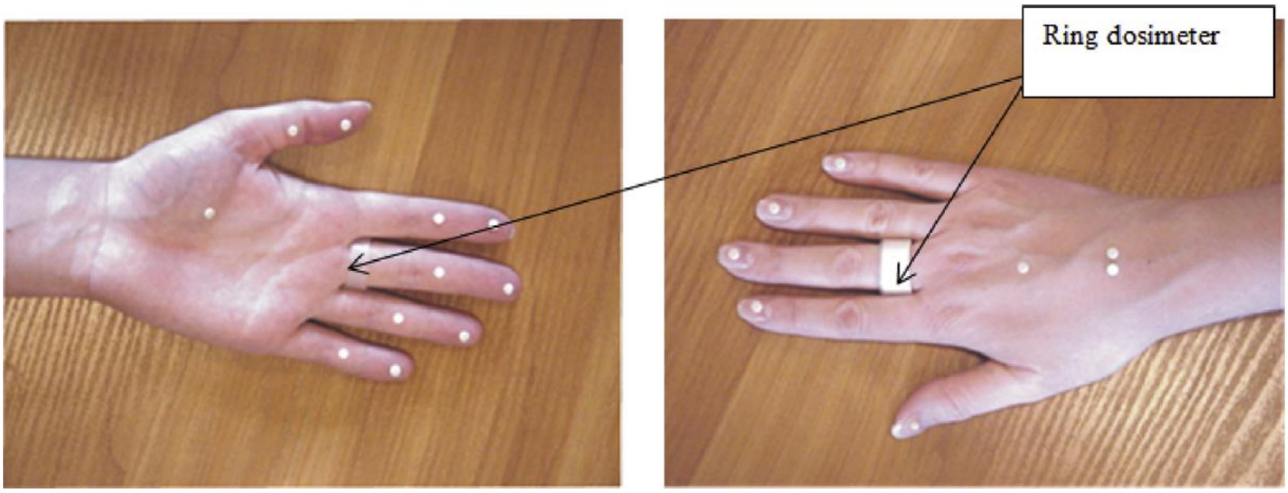


Fig. 4. Positioning of TLDs in research project performed in Poland [53]

In 2015 similar research was performed in Kuwait Cancer Control Center (KCCC) [54]. The data from occupational monitoring was collected over a period of 1 year and the estimations were carried out on different classes of the workers – hot-lab, NM and PET physicians and nurses. The doses between the individuals in the matching sub-group appeared to be similar. Though, as can be seen in Fig. 5, the staff from the hot lab receives biggest doses for the extremities – 120 mSv/year, due to the production, preparation and dispensing of radioactive materials. For all staff categories, the total body dose and the doses to the eye lens did not exceed 4.0 mSv. The use of proper shielding and automated injection systems are recommended by authors to reduce the doses. Also, the rotation of the personnel in different areas of work stations is considered [54].

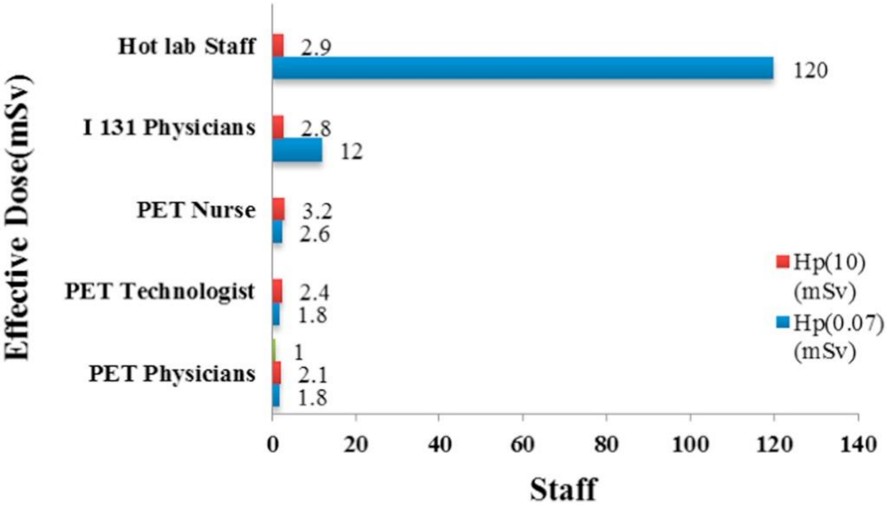


Fig. 5. Occupational doses between different staff groups [54]

Measured and normalized to the control radioactivity, fingertip doses varied in the broad interval – 23 – 360 μSv GBq^{-1}. Smaller variations (13 – 52 μSv GBq^{-1}) were found for the doses measured at the finger base. Two staff members received doses up to 2000 μSv GBq^{-1} at the tip of the finger, and 999 μSv GBq^{-1} at the base of the finger. Low working habits and a deficiency of protective gear were linked to these elevated values. In general, the largest dosages were seen throughout preparing and dispensing, but staff exposure was lower during only preparation or administration. The figure below, shows a summary of mean and median doses which were measured at the tip and at the base of the finger, which were published in the literature [17].

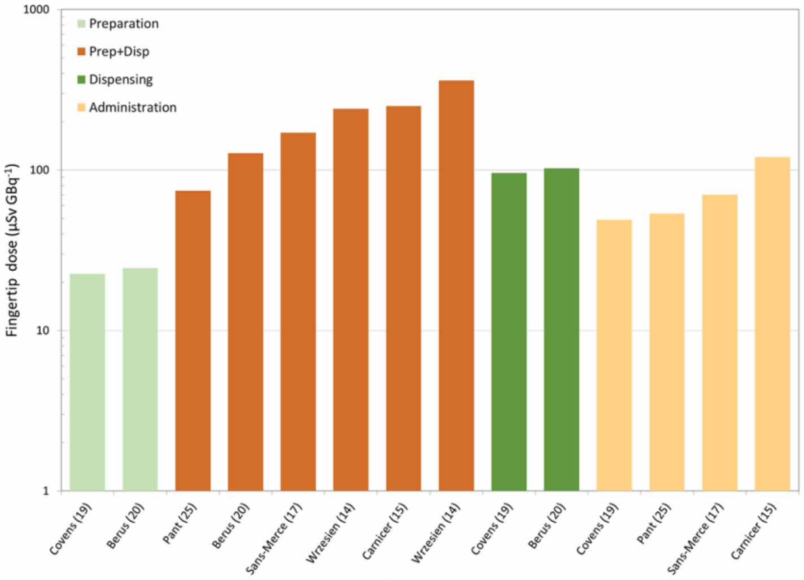


Fig. 6. Reported fingertip doses from different manipulations of ^{99m}Tc, reported in literature [17]

In 2019 EU survey EURADOS reported how European countries are monitoring doses to the extremities. Thus, mean measured annual doses were reported. In the third table mean yearly doses from 14 EU countries are provided. The highest annual mean dose was reported in France – 28.8 and the lowest mean dose was reported in Luxembourg – 4.5, on the other hand, in Luxembourg only two workers were monitored in this field. From 1 to 2 workers in France, Germany, Spain and Switzerland exceeded the international limits of 500 mSv per year. In Lithuania annual mean reported dose is 10.4 mSv [7].

Table 3. Mean annual extremity doses in Europe in 2019 [7]

Country	Mean annual dose for extremities (mSv)	Number of workers			
		> 5 mSv	> 50 mSv	> 150 mSv	> 500 mSv
Belgium	8.5	109	20	1	0
Estonia	8.3	15	0	0	0
France	28.8	1292	344	28	1
Germany	13.7	1840	386	39	2
Greece	11.8	73	21	5	0
Iceland	10.5	5	1	0	0
Ireland	5	42	5	0	0
Lithuania	10.4	16	3	0	0
Luxembourg	4.5	2	0	0	0
Netherlands	13	214	44	2	0
Poland	7	93	15	0	0
Slovakia	7.8	87	11	4	0
Spain	21.3	795*	223	29	1
Switzerland	20	275	82	17	2

A number of studies have looked for the best position when monitoring the extremity exposure. Although, fingertips of the ND (non-dominant) hand sometimes seems to be the most exposed, it is frequently impossible or impractical to monitor this area directly. As a result, routine dosimeters are placed in positions that are convenient, and maximum values of the doses are calculated when applying multiplication factors. In ideal case, multiplication factor should be calculated individually for each worker, due to different work practice [17].

NM workers consists of a variety of people, who are exposed to low amounts of ionizing radiation on the job [23]. In the NDRs (National dose registries), there are still very few instances of high measured dose values. The increased usage of ring dosimeters, particularly in France and Spain, could explain the rise in registered doses. The NDRs are available in almost all countries and despite the fact that the form did not ask about the utilization of the ring dosimeters versus wrist dosimeters, it is obvious that TLD ring is more widely used than it was back in 2005. Monitoring of the doses with a ring may be the most feasible method, but according to ORAMED recommendations for NM, it may underrate the maximum extremities dose values by a factor of six [7].

In the image below, the ratios between fingertip maximum dose and a ring dosimeter dose are visualized, as reported by different authors. The wrist maximum dose ratios were not taken into an account because they were much higher varied in the broader interval than ring dosimeters. In literature [17], it is reported that wrist doses might be up to 20 – 25 times lower, than the doses measured by a ring dosimeter.

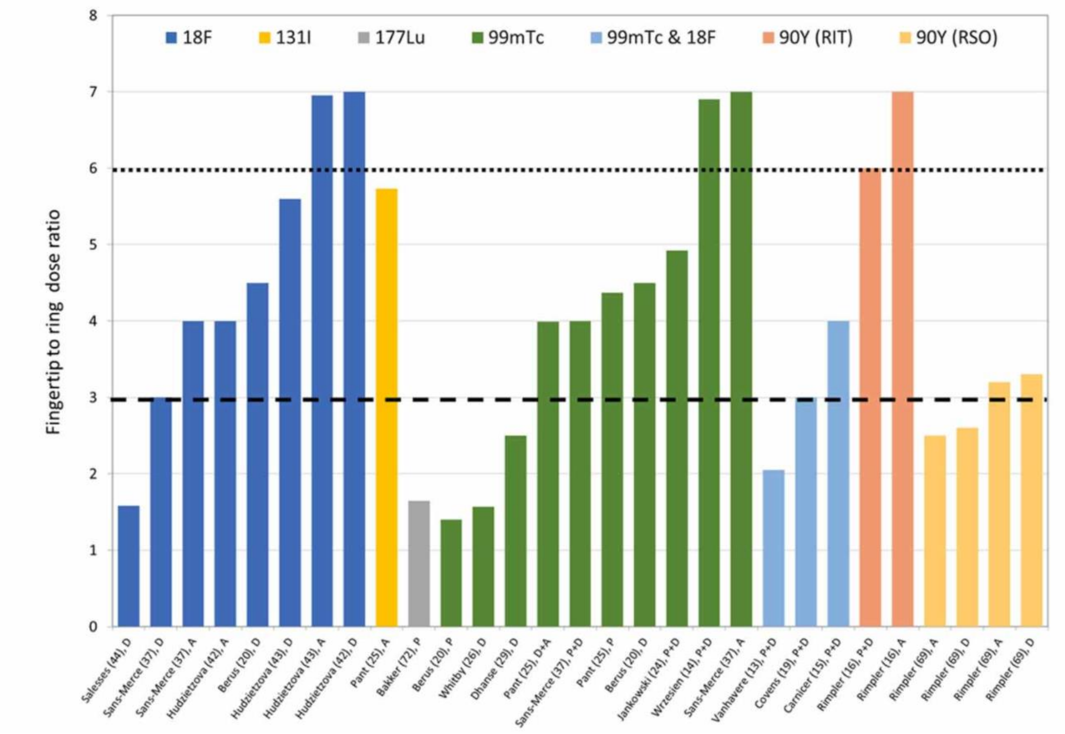


Fig. 7. Dose ratios between fingertips and ring dosimeter, reported in the literature. The ORAMED and ICRP recommended general monitoring ratios are represented by horizontal lines, respectively [17]

The optimum position for extremities monitoring is as close as realizable to the location, where the maximum dosage could be established to meet with the limit of dose restriction for the skin. The ORAMED project published the frequencies, of the positions with maximum collected dose values in the preparation and administration of ^{99m}Tc for both of the hands simultaneously (Fig. 8). As can be seen from the figure in 2010 according to publication of the ORAMED, index fingertip usually gets maximum dose [6]. Though, it is not the most comfortable position for routinely monitoring, thus it was suggested to put on a ring dosimeter on ND index finger and as mentioned before, the correction factor of 6 was recommended [17].

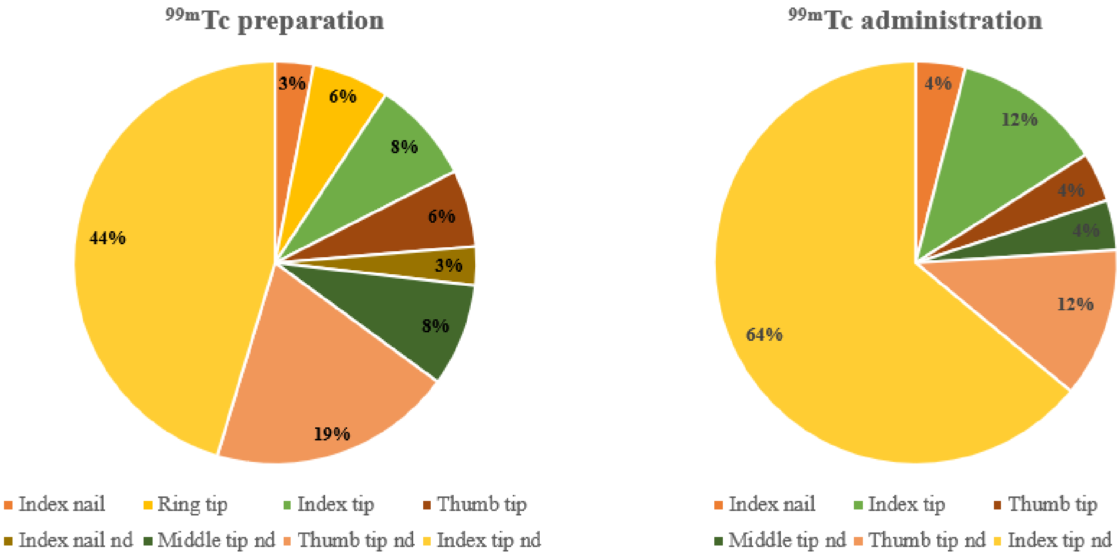


Fig. 8. Frequencies of maximum doses collected in certain monitoring positions [6]

It was also shown that index tips of both: dominant and not dominant hand get maximum cumulated dose during preparation of Tc-99m labeled pharmaceuticals, however during administration of radiopharmaceuticals maximum cumulated dose was received by index tip of the dominant hand and thumb of the non-dominant hand [6].

The study performed in Bangladesh in 2019, tried to determine which hand is more exposed to ionizing radiation, when handling lots of ^{99m}Tc, ^{125}I and ^{131}I. 40 TLD chips were used for the investigation, which were worn daily on middle fingers of each hand, moreover, their whole-body doses were measured for the comparison. The average absorbed dose, for the right hand was higher (12.7 ± 12.9 mSv), than for the left hand (10.7 ± 8.2 mSv). The authors explain this result as the right hand being more active while handling radiopharmaceuticals. The highest whole-body dose collected was – 36 mSv, while for the extremities – 3 mSv, which means that whole-body dose measurements is at least 12 times lower than measured dose for the hands [55].

Radiation shielding is a fundamental concept that must be taken into an account in every situation that uses ionization. A well-designed shielding strategy, limits the quantity of radiation that employees are exposed to and minimizes radiation exposure to tolerable levels, while causing minimal damage to live tissue [58]. Despite both positive and negative arguments, lead aprons are commonly used in radiology operations. The protection effectiveness of the lead apron was tested for ^{99m}Tc and ^{18}F in a published research. Despite the significant dosage reduction by the ^{99m}Tc, little protection against ^{18}F was reported [26].

Nuclear medicine technicians collect higher doses to the fingers when preparing and dispensing radiopharmaceuticals. As a result, the usage of automated injectors can considerably benefit for attempts to reduce occupational dose. The application of safety precautions and accessories, as well as correct reason of nuclear medicine treatments and accurate optimization of the technique, will protect the personnel from preventable radiation-induced risk of oncological diseases and the tissue reaction danger [22]. Vials must be protected throughout all times, either with tungsten vial shield or lead pots, as advised by radiopharmacies. When dispensing as well as drawing up injections, syringe shields can limit finger dosages by up to 85 %, it should be used whenever possible. When radiopharmaceuticals are injected, the fingers are also irradiated, and doses could be higher whether the syringes are covered well enough or not, moreover, if the fingertips are positioned on the needle while performing an injection. When administering injections, a so-called butterfly syringe can be used to decrease finger exposure. Automated systems created for dispensing or drawing up radioactive solutions, particularly with radionuclides used for PET, can significantly lower dosages where possible, albeit cost may be an issue [57].

As reported in the literature, lead partition, syringe and holder shields have efficiency more than 90 %, and they are the ideal protection used in nuclear medicine to preserve against radiation sources, utilized in NM. The measured efficiencies of the protective equipment can be seen on the figure below. The syringe holder shield provides the maximum protection and is the most efficient. Shields of greater thicknesses provide higher efficiency against ^{99m}Tc, according to the dosimetric approach. On account of a greater amount of photon interactions with the shield atoms [58]. The ORAMED study estimated that shielding with lead or tungsten of 2 mm is generally enough sufficient for ^{99m}Tc [18].

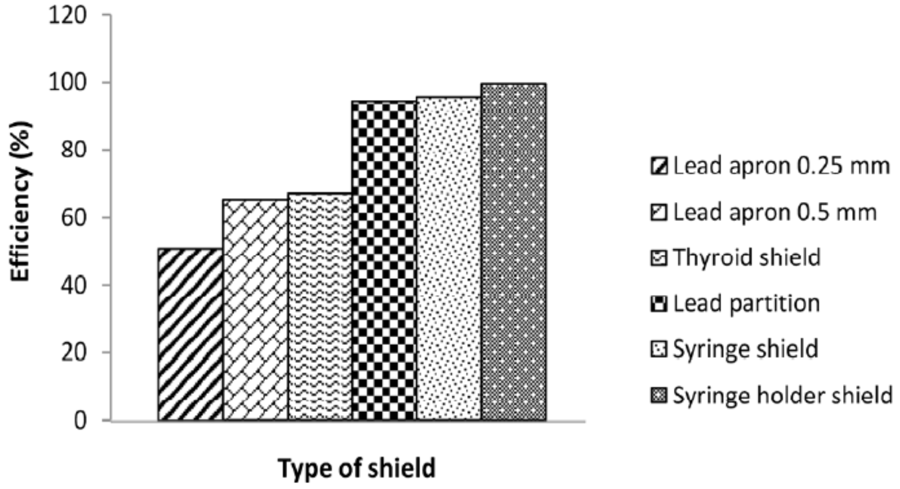


Fig. 9. The dosimetric approach was used to determine the efficiency of NM shields against a $^{99}Tc^{m}$ source [58].

The doses received by the extremities usually depend on many various factors, such as the period of time when holding the syringe, flow of the procedure, count of them per day, and of course, years of working experience. Working quickly is said to be ineffective; instead, using shields or extending the distance is more beneficial. More important than the experience level of the operator is training and instruction in good practices (such as procedure preparation, rehearse actions using non-radioactive sources). Moreover, many studies reveal that maximum doses are usually connected to bad working practices, meaning staff should optimize working habits [6].

European Radiation Dosimetry Group (EURADOS) prepared a survey for EU countries to determine, how countries ensure occupational exposure limits in NM departments. The quiz is believed to be beneficial for updating information and gain insight on the recommendations in different countries. Thirteen of them are EU members and thus, must follow the EU BSS Directive, while non-EU members do not [7]. When individuals in the NM field are exposed to radiation, they are monitored using personal dosimeters, and the measurement results are generally kept in digital format [23]. More than half of the participants that responded gave data on average annual extremities doses, which differ in between 4.5 mSv to 28.8 mSv. In 2018, several workers in Germany, France, Switzerland, and Spain exceeded the 500 mSv exposure limit. For PET employees in Switzerland, these numbers were 552 and 562 mSv, respectively [7].

The most popular guidance is to place the extremities dosimeter on the index of ND hand, while the sensitive section is facing the inside of the hand. On the other hand, the dominant hand is suggested, in two countries (Iceland, Poland), while, Croatia recommends to wear dosimeter on the middle finger rather than the index finger. The majority of responders do not lay out the information on the commonly used position in practice. All of the countries, which participated in the survey, have TLDs available for dosimetry [7].

EURADOS survey revealed that ten out of sixteen European countries have declared defined advices on how and where to wear ring dosimeter. Some recommendations are not throughout, meaning that, there is missing information about selection of hand or a finger. The most commonly suggested recommendation is wearing ring dosimeter on index on ND hand. In comparison, Poland and Iceland, have the recommendation is to put a ring dosimeter on index on the dominant hand, while Croatia and Lithuania have the recommendation to wear dosimeter on middle finger. Moreover, the correction factors for extremities monitoring differ from 2 to 6 in different countries [7].

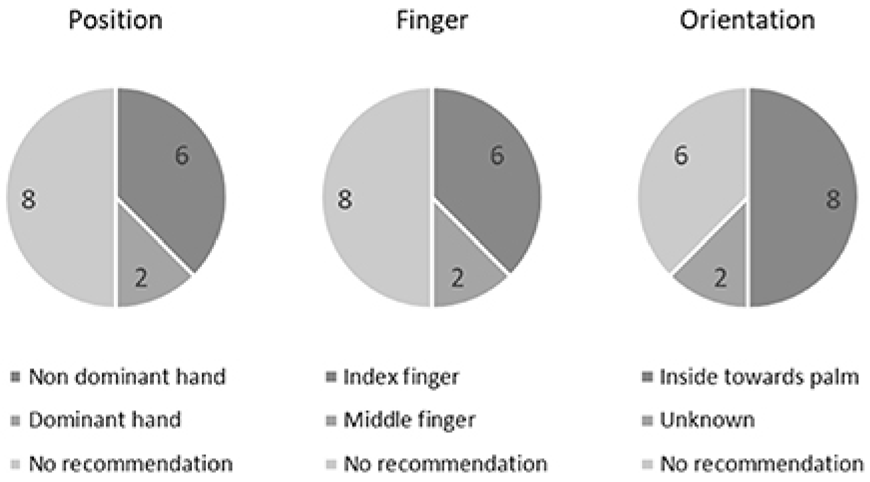


Fig. 10. Number of the countries, representing the recommendations on positioning the extremity dosimeters [7]

1.7. Investigations of radiation exposure with hand phantom

In 2011, a research was performed using a mathematical hand phantom with fixed and flexible parts, which allows for customizable anatomy. The experimental set-up, which includes a wax hand phantom, a syringe, and TL dosimeters at various locations of the hand, as well as the accompanying voxel model with the mathematically created hand, is depicted in the image below. The scenarios were simulated from the results of the ORAMED project, these outcomes were simulated using extracted 3D coordinates of various points in order to move and regulate the phantom, while the syringe was simulated manually [59].

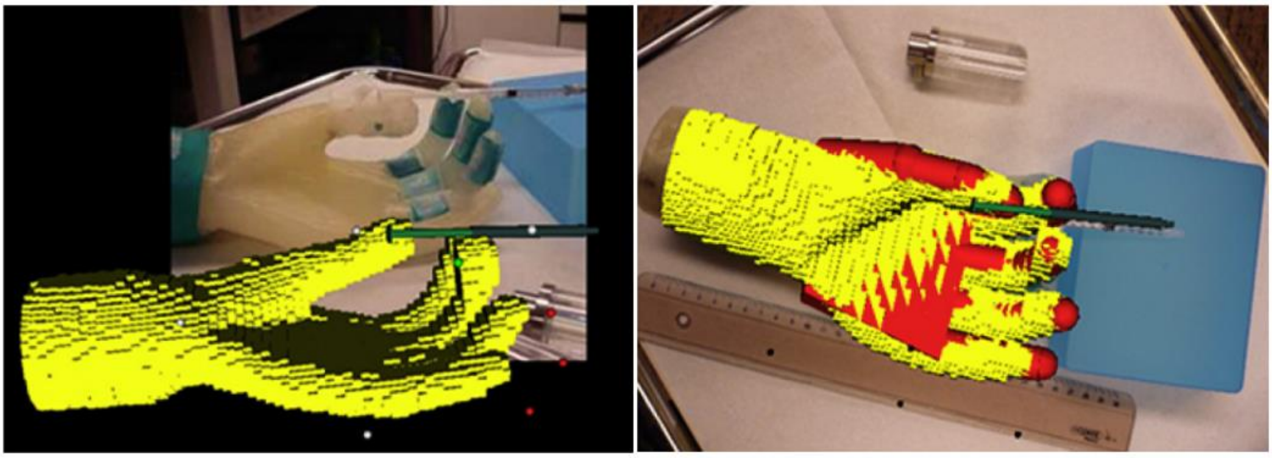


Fig. 11. Mathematical phantom created by the images of the vowel phantom [59]

The findings of the simulations were compared to the ORAMED data and is represented in Fig. 12. The dose difference due to various syringe positions could be nearly an order of the magnitude as can be seen in an example of the middle finger nail. Variation between voxel phantom dose values and obtained values from simulation may be attributed to the geometry difference. Nevertheless, variations in position, obviously, have a significant impact on simulation and measurement findings.

These kinds of visualisations can be very useful about providing information about hand positions and motions, thus improving protection and safety of the staff [59].

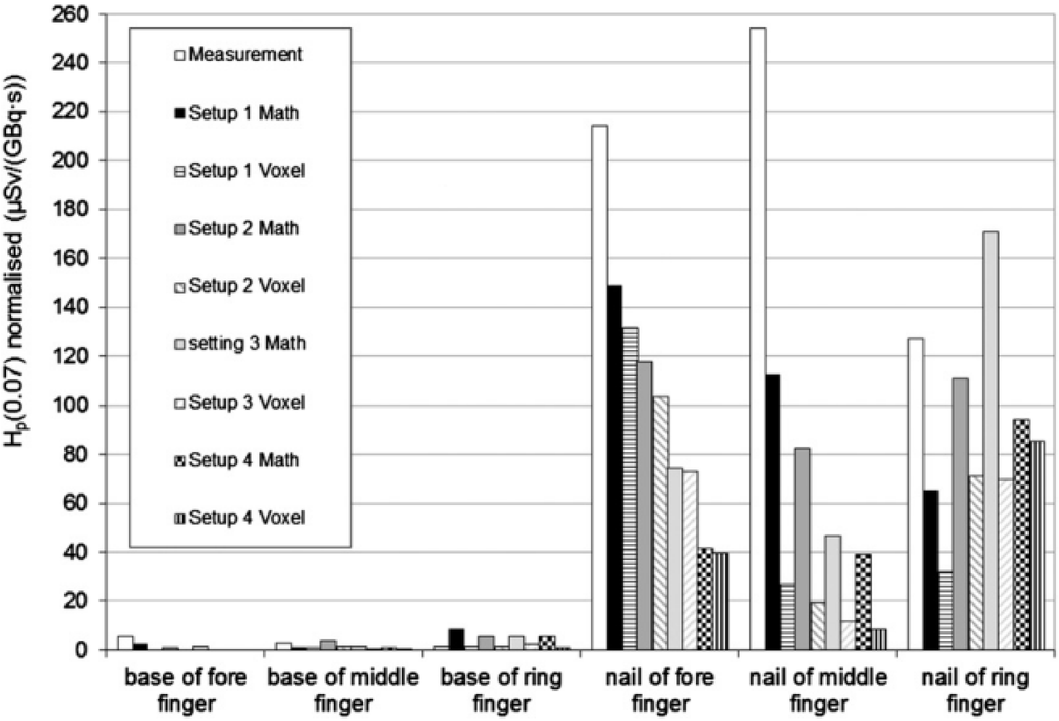


Fig. 12. Mathematically simulated dose values in comparison with voxel phantom [59]

Similar project, also imitated actions of the technologist with an artificial hand. For the research, five wax hand phantoms in a realistic size were casted, each of them imitating different hand motions, when manipulating radiopharmaceuticals. As it can be seen in the figure 13, first two phantoms from the left were created for imitating an injection (pushing the piston and holding the syringe), third and fourth images from the left are showing phantoms which were moulded to simulate the manipulations of the syringe and the last one was casted to imitate the moving of the vial. Phantoms then were scanned with a CT, segmented and then inputted into a software. The soft tissue regions of 140 µm thick, of 1 cm^2 were added, which represented TLDs positioning. Also, another small amount of tissues was simulated in order to replicate gloves [60].

Fig. 13. Created wax phantoms in different positions for dose simulation [60]

Using Monte Carlo simulations, it was found out that, relatively modest displacements (on the range of one to a few cm) of the ionizing source with regard to the position of the sensor can result in dosage reductions ranging from 0.5 to 3. The simulations calculated the dosage decrease due to correct shielding throughout radiopharmaceutical preparation and the convenience of using forceps as an extra safety element, even when using shielded sources. Nevertheless, using these simulations, dose maps were made, which can also be used for safety measures of the staff. The dose mapping in Fig. 14 indicates a peak of 41 Sv/GBq.s on the inner surface part of the index finger and middle finger.

The nearest TLD dosimeter, which is positioned on the index nail, underestimates the dose number by less than 20 %. That means, given the basic approximations of a model, the results are close from the predicted values and location of the dosage maximum, on the palm in the majority of cases [60].

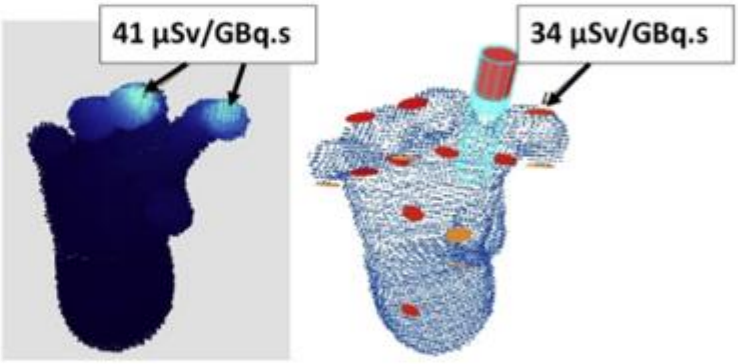


Fig. 14. Dose mapping on the left and $H_p(0.07)$ on the right that was calculated in simulated position of TLDs [60].

1.8. Literature review summary

Nuclear medicine workers are experiencing radiation exposure in daily occupational tasks. The personnel are receiving low whole-body doses, when manipulating radiopharmaceuticals, as well as high doses to the extremities. The limits, set by authorities are usually followed and accomplished, though the most difficult task is to measure doses to the fingertips, which might surpass the international limit, which is 500 mSv per year, therefore it may have an impact on health of the worker. The experts already have agreed on possible biological consequences that include cancer and other non-malignant diseases.

The most challenging issue in monitoring of extremities doses is to foresee which parts of the hand or fingers are mostly exposed to ionizing radiation. Usually, for monitoring doses to the extremities TLD ring dosimeter is used. The recommendations on how and where to wear a ring dosimeter depends on national regulations. In Lithuania, it is recommended to wear a ring dosimeter on the most exposed finger. Nevertheless, monitoring of the extremity doses remains very important. As it can be understood from various literature sources, the main reasons for higher doses to the fingertips, typically are: bad working habits, rushing, not using provided shielding, and lack of experience. To meet the standards, it is advised to train workers, adapt good working practices, and even rehearse the procedure actions.

2. Materials and methods

2.1. Equipment used in radiology department

Measurements were performed in the Radiology department of the Hospital of Lithuanian University of Health Sciences (LSMU) Kauno Klinikos. The exposure doses of the whole-body and fingertips were assessed for technologists that are preparing and administering radiopharmaceuticals for different nuclear medicine imaging procedures, which include PET, SPECT and imaging with a gamma camera. PET is a sensitive imaging technique that is based on injecting prepared radiopharmaceuticals to the patients, which are positron-emitting radionuclide tracers. Image acquisition in PET technique, is based on the coincidence detection of two gamma rays [61]. The detectors absorbe the energy, which later is emitted as a light, that is visible and can be detected via photomultiplier tubes. The signal of the light is transformed into an electrical current, proportionate to the energy of the incident photons [62]. PET scanner, used in Kaunas Clinics is pictured in the image below.

Fig. 15. PET scanner in Kaunas Clinics department of radiology

Gamma camera (Fig. 16) is a medical device that registers gamma rays emanating from a patient, which has been injected with a radionuclide substance. The detector in a gamma camera is commonly made up of a collimator, a scintillator matrix, and a photomultiplier tube. Gamma rays are emitted by a radioisotope administered with a radiopharmaceutical injection to a patient prior to the study, which is distributed in the body, depending on the pathology and the properties of the drug solution itself. A 2D (two-dimensional) image is obtained from the distribution of the recorded gamma rays. SPECT is similar technique to the gamma camera, and produces slices throughout the human body. Radioisotopes used for gamma cameras and SPECT are the same, because the detection techniques are created on the same conception. The ^{99m}Tc radioisotope, which has a photopeak of 140 keV, is the most commonly utilized radioisotope [63], [64].

Fig. 16. Gamma camera in Kaunas Clinics department of radiology

SPECT is a technique that integrates a gamma camera rotation with a computerized calculating system to obtain cross-sectional images. A schematic illustration of SPECT in a clinical setting can be seen in the picture below [65]. Radioisotopes used for SPECT are limited to the particular that emit gamma rays (such as ^{201}Tl, ^{99m}Tc, and ^{123}I) with an energy range that is suitable for the gamma camera. This technique is used in many nuclear medicine tests, which use single photon emission tracers in clinical practice. A gamma ray detector includes a large block of scintillator crystals. A multihole collimator is arranged on the front side of the system to give a spatial correlation of the detected incidents [66].

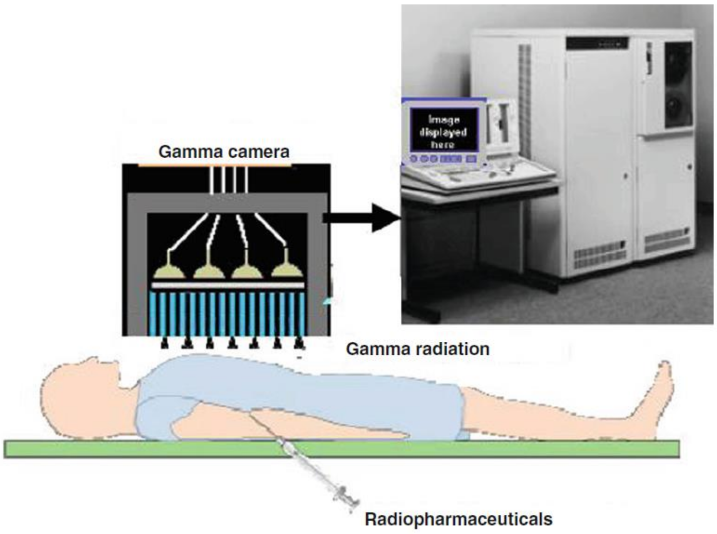


Fig. 17. SPECT schematic setup [65]

Radiopharmaceutical preparation laboratory (hot-lab) is a room equipped with a fume cupboard (Fig. 18) for the preparation and dilution of radiopharmaceuticals as well as measuring calibrators for assessment of the activity of prepared solutions. The fume cupboard routinely has a lead shielding, which is applied to the sides, countertop, and has a sliding chest guard to protect the working operator. The cupboard must be used for technologist and environment protection as well as keeping prepared radiopharmaceutical from contamination. In the hot-lab, staff performs manipulations with high-levels of radionuclide activities while the hands and the fingertips are exposed to higher levels of radiation.

Fig. 18. Fume cupboard in Kaunas Clinics Nuclear Medicine department

2.2. Dosimetry

Four technologists of Kaunas Clinics, Clinic of Radiology, working with open ionization sources, participated in this research. The whole-body dose was recorded and evaluated using the "Landauer In Light" OSL personal dosimetry system: passive full-body dosimeters (A_2O_3: C capsules; sensitivity 0.05 mSv – 10 Sv) worn under the protective apron in the chest or lumbar region and electronic personal dosimeters "POLYMASTER" for obtaining dynamic dosimetry measurements. Hand doses were recorded using a personal ring thermoluminescent dosimeter (LiF: Ti, Mg) worn on one of the fingers, which technologist chose by a personal preference, (dosimeter position – inside of the palm) (Fig. 19). Thin (< 100 mg/cm^2), hypersensitive ^{7}LiF: Mg, Cu, P dosimeters (TLD-100H) were used to record fingertip doses. The calibration of the dosimeters was done using a flat source of Co-57 (122 keV). Because these detectors are compact and do not cause major discomfort to the employees, they are the best instrument for extremities measurements right now.

Fig. 19. TLD and ring dosimeter positions for measurements

Additional dosimetry measurements were performed with the prosthetic hand in order to simulate the actions of the technologist when preparing ^{99m}Tc radiopharmaceuticals in a hot laboratory (injection of the solution into the syringe). Eighteen TLD-100 (LiF:Mg,Ti) chips, packed into the plastic bags and were attached to the hand phantom in different places (Fig. 20). The TLDs were chosen due to them being tissue equivalent (with effective atomic No. of 8.2, which is equivalent to No. 7.4 for tissue), wide linear response spectrum (10 µGy – 10 Gy). Furthermore, TLDs have a great sensitivity for very low dose assessments. The syringe, filled with the ^{99m}Tc labelled radiopharmaceutical was held for 25 seconds in a fume cupboard in order to simulate the procedure.

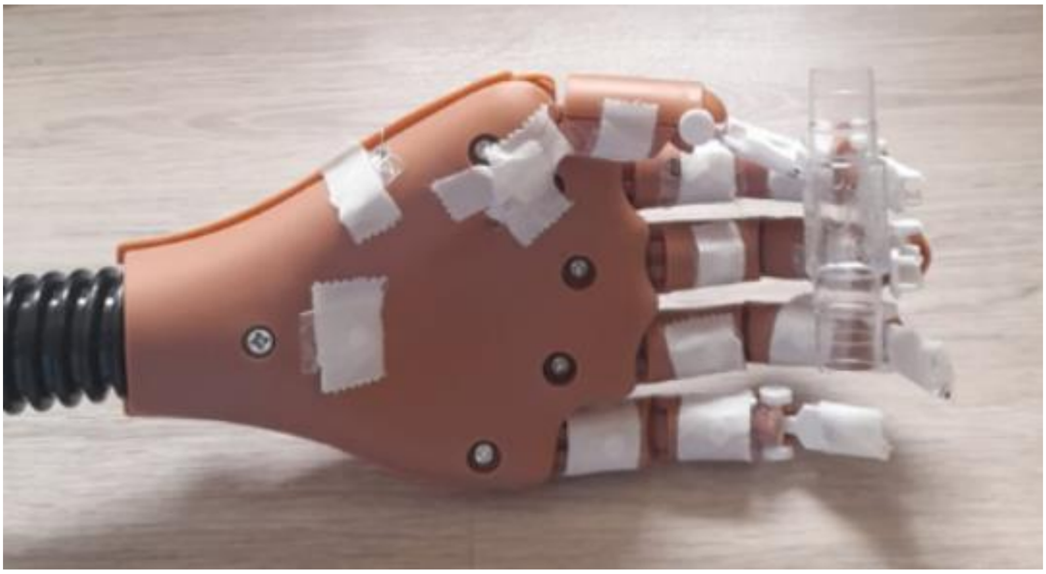


Fig. 20. Prosthetic hand with attached TLDs

Dosimeters were calibrated with known doses for evaluation of the results. Dose used for calibration of the TLD dosimeters – 1 mSv. The TLD-100 chips were placed next to the Co-57 (half-life of 271.8 days) source for the calibration (Fig. 21). The dosimeters, placed on the source plate, were left for a certain period of time – to obtain defined doses for calculation of the results, the dose rate on the surface of the Co-57 source was 1.55 mSv/h.

Fig. 21. Co-57 source, used for calibration

After irradiation, TLD dosimeters were read out using RIALTO TLD reader. The readout procedure was performed in Kaunas University of Technology. Dosimeters were placed in a detector carrousel with thirty heating trays. When heated, TLD dosimeters produced light, which enters the photomultiplier tube, that is used to convert light into a current signal, which is amplified and after that displayed. The system is connected to a pure hydrogen tank, which provides atmosphere to eliminate luminescence. The output of the light is proportional to the amount of radiation [67].

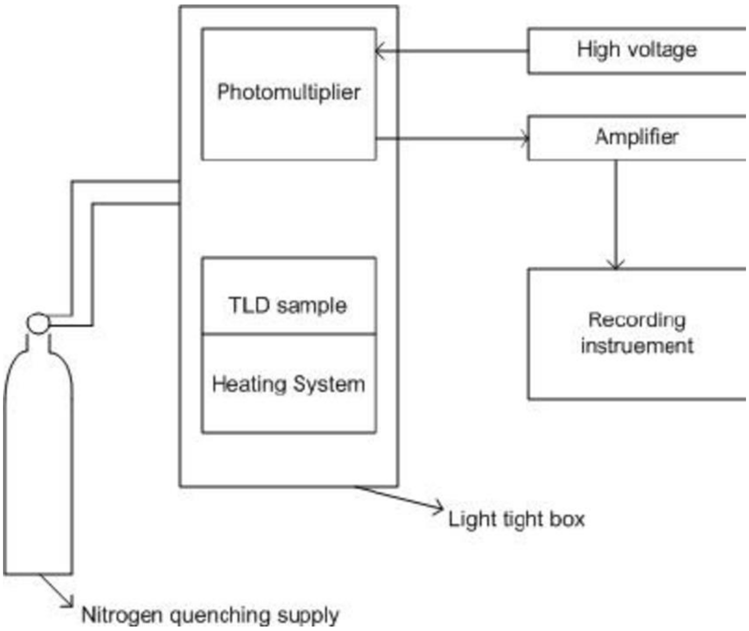


Fig. 22. Schematic view of TLD reader system [67]

2.3. Radiopharmaceuticals

The radiopharmaceutical injection procedure consists of intravenous shot administration of the solutions to the patients. The technologist attaches the product to a catheter, injects the radiopharmaceutical, disconnects the syringe and withdraws the catheter from the patient. When a patient is injected with a certain activity, he/she becomes a source of ionizing radiation. In the vicinity of the injected patient, the exposure dose of the worker increases not only to the limbs, but to the whole body.

In the Department of Radiology of LSMU Hospital Kaunas Clinics ^{99m}Tc and ^{18}F (FDG) radionuclides are used for diagnosis of the diseases. ^{99m}Tc is drawn into syringes manually, the injections are also performed by hand, while ^{18}F procedures are done by using automatic injector. Manual injectors in the nuclear medicine department are depicted below.

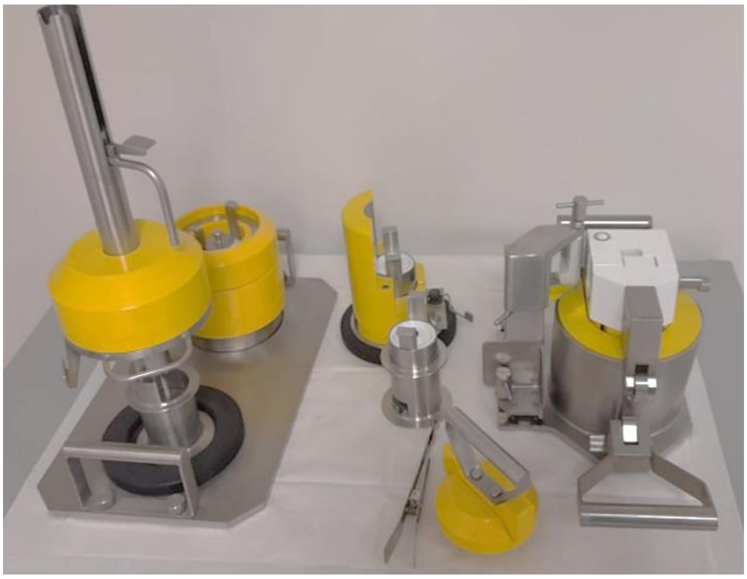


Fig. 23. Manual injectors in Kaunas Clinics

Intravenous FDG injections to patients are performed using the “IRIDE” automated patient injection device. The prepared radiopharmaceutical (FDG) is delivered to the workplace in a protective container. With the help of a medical physicist, a radiology technologist places a container into an automatic device, which is shielded from ionizing radiation. Using the injector software, the patient information is entered, the required activity is calculated, and the radiopharmaceutical is injected. Later, the system is connected to the previously inserted catheter to the patient. Regarding, the high activity involved, the technologist moves away from the injected person during the procedure, and after the shot, the catheter is removed from the patient. In average, eight procedures are performed per one working day in Kaunas Clinics, average activity of the injection – 350 MBq.

^{18}F is a positron-emitting cyclotron-produced fluorine radioisotope (half-life of 109.7 min). It enables for the labelling of a variety of molecular tracers that may be observed in a period of a few hours of injection (usually 3 hours). FDG (^{18}F-2-fluoro-2-deoxyglucose) is a glucose equivalent that is absorbed by living cells via $C_6H_{12}O_6$ transporters in a cell membrane and then incorporated into the normal glycolytic pathway [68]. The uptake of the radiotracer in the glycolytic metabolism provides the diverse use of FDG in oncological indications. Beyond cancer detection, FDG is used in infection detection, central nervous system diseases as well as cardiovascular disorders [69].

Exposure for each working day, when working with ^{99m}Tc depends on the number of the patients and the activity of the Mo/Tc generator that day. Usually, Mo/Tc generators are calibrated on Monday, so on this day the generators activity reaches 30 GBq. In the beginning of the day, elution of the generators is performed, using physiological solution, pure saline-free ^{99m}Tc solution is isolated from generator, with the volume possibilities of 4, 6 and 8 ml. The smaller the volume, the higher the activity concentration. Radiopharmaceuticals are then prepared according to a scheduled plan by adding a drug to the ^{99m}Tc solution, that accumulates activity in certain organs. A technician working in the technetium solution injection procedure, provides intravenous shots of radiopharmaceuticals to the patients into a syringe by a colleague working in the hot ^{99m}Tc laboratory. The technologist attaches the reconstituted product to the catheter, injects the solution, disconnects the syringe, and withdraws the catheter from the patient. The radiopharmaceuticals are routinely prepared in the morning, due to high number of patients for bone scintigraphy procedure, the solutions are made two times a day. Previously prepared ^{99m}Tc radiopharmaceuticals in a fume cupboard are pictured in Fig. 24.

Fig. 24. ^{99m}Tc radiopharmaceuticals prepared in the morning

The nuclear characteristics of ^{99m}Tc are well established, making this radionuclide optimal for radiopharmaceutical applications. It has a half-life of 6.0067 hours and has emission of 140 keV gamma photon. These characteristics make it simple to make ^{99m}Tc radiopharmaceuticals earlier on, delivering them to the patients and to obtain high-quality images [70]. Moreover, the widespread use of ^{99m}Tc is regarding the ^{99}Mo/^{99m}Tc generators, which allowed the shipment worldwide, as well as its diverse chemistry, resulted in various ^{99m}Tc radiopharmaceuticals developed, which are suitable for many procedures (different ^{99m}Tc solutions, used in Kaunas Clinics are provided in the table below together with their medical applications) [71].

Table 4. ^{99m}Tc radiopharmaceuticals and their usage in medicine

^{99m}Tc Radiopharmaceutical	**Medical Application**	**Average injection activity, MBq**	**Activity during preparation, GBq**
^{99m}Tc-Sestamibi	Cardiac patients (active exam while patient is riding a bicycle)	250	not lower than 6.5
^{99m}Tc-Sestamibi	Cardiac patients (passive exam)	600	not lower than 6.5
^{99m}Tc-methyl diphosphonate (^{99m}Tc MDP)	Bone scintigraphy	550	from 6.5 to 8*
^{99m}Tc-Nanocolloid	Lymphoscintigraphy	100	from 1.0 to 1.5
^{99m}Tc-DMSA	Thyroid imaging	110	from 1.0 to 1.5
^{99m}Tc-MAG3	Kidney scan	200	from 1.0 to 1.5
^{99m}Tc-DTPA	Lung perfusion	160	up to 1.7
^{99m}Tc-Tektrotyd	Neuroendocrine tumours	500-700	~1.5

*due to high number of patients, preparation is repeated twice a day

3. Results

3.1. Whole-body dose assessment

The results were collected at Radiology Department of Kaunas Clinics. Exposure of nuclear medicine workers was studied in three aspects: whole-body exposure, hand exposure, and doses to the fingertips. With the help of an electronic dosimeter, dynamic information about the whole-body exposure dose, received by the technologist, in a working day was recorded. The obtained data allowed to propose and implement daily dynamic dose maps of the technologists, in practice, which allows for monitoring of the cumulative curve of radiation doses in real time. By analysing the dose maps data, it is possible to estimate the exposure doses of the worker, from different working positions. Moreover, dynamic dose monitoring, allows to detect deviations from average doses and to apply adequate corrective or protective measures to the personnel, including the ability to perform one operation or another. When higher accumulated dose peaks were detected during the day, later the reasons were analysed. The examples of higher dose causes are shown in the table below.

Table 5. Doses received by NM technologists during working day activities

Technologist	**Date**	**Accumulated dose during the day, µSv**	**Reason of the higher dose**
No. 2	8th of July	9.6	Long period of time spent with a radioactive patient due to the patient's condition (positioning of the patient on the couch)
No. 4	17th of September	14.36	Higher number of treated patients per day as usual.
No. 1	3rd of November	7.76	Close contact with a radioactive patient (holding the patient, who ran in panic)
No. 4	27th of November	9.64	Syringe fixation problems while connecting to a catheter

According to the schedule, which is provided by the institution, one technologist, during the working week, performs tasks in only one of the following positions:

1. Works in a procedure room (inserts catheters);
2. Works in ^{99m}Tc hot laboratory (performs preparation of radiopharmaceuticals, injection into the syringe);
3. Assists in the ^{99m}Tc hot laboratory (delivers radiopharmaceuticals, prepares the necessary equipment for a colleague, and then performs injections for heart patients);
4. Works in the ^{99m}Tc operating room (performs injections of all remaining radiopharmaceuticals with ^{99m}Tc into patients);
5. Performs cardiac scans (^{99m}Tc);
6. Performs all other scans (^{99m}Tc);
7. Injects FDG (^{18}F) to patients;
8. PET / CT scanning.

In this project, the working positions of the technologists were selected taking into an account the activities of the radionuclides used and the contact of the radiologists with the radiopharmaceuticals. The three job positions, where technologists might be exposed the most, were selected: ^{99m}Tc hot laboratory, ^{99m}Tc solution injection procedure room and fluorodeoxyglucose ^{18}F injection procedure room. It is useful to mention that, after a week of working in one position, the NM technologists rotate according to a pre-arranged schedule and do not work in the same position for longer than one working week.

Dose monitoring was performed for four technologists working in NM. For evaluation of the results and differences between dosages from one technologist to another, one of the most important factors is experience of the worker. The longest working period in nuclear medicine department, from analysed technologists is 17 years counting to the start of the investigation and it is operator no. 1. Meanwhile, fourth technologist has the shortest experience in NM, which is 3 years. The time period of other analysed workers is 8 and 5 years for 2nd and 3rd technologists, respectively. The highest yearly average whole-body $H_p(10)$ dose was recorded for the 4th operator – 0.93 mSv, while the average dose for the hands $H_p(0.07)$ of the same technologist was 65.68 mSv. Consequently, the lowest $H_p(10)$ is for the 3rd technologist – 0.7 mSv, as well as mean $H_p(0.07)$ – 39.19 mSv. Similar $H_p(10)$ research project was performed in Canada, when mean annual doses were obtained in a period of few years (2015 – 2019). The reported average yearly whole-body doses for nuclear medicine technologists were in a range of 0.19 – 3.21 mSv, while average yearly doses to the hands were in a range between 0.33 to 70.55 mSv [72]. Another research showed similar results, in UAE $H_p(10)$ was assessed in a few hospitals, and an average dose for all radiation technologists were 0.63 mSv [73], which is very close to mean average whole-body dose of a third technologist, as assessed during this project. In addition to these results, Serbian research, also posted mean whole-body yearly values for nuclear medicine technologists, which range in between 1.2 mSv to 3.4 mSv [74]. The average annual effective doses of NM technologists were usually distributed from 0.75 to 1.6 mSv as reported by UN Scientific Committee on the Effects of Atomic Radiation [26], which is, also very similar results, with the numbers obtained in this research.

During this project, whole-body doses were also compared, not only between different technologists, but also, between already mentioned “hottest” working positions. As can be seen from table no. 7, the whole-body dose obtained in a hot-lab is lower in comparison with the exposure of the $H_p(10)$ when working in both ^{99m}Tc and ^{18}F injection rooms. The explanation would be, that in a hot-lab, a nuclear medicine operator is standing behind a protective lead-glass and wearing protective equipment, and only the hands of the employee are in a contact with the activity, while in a procedure room, workers come in close contact with radioactive patients.

Table 6. Whole-body doses accumulated when working in different positions

NM technologist	**^{99m}Tc hot-lab**		**^{99mTc} procedure room**		**FDG ^{18}F procedure room**	
		Whole-body dose, $H_p(10)$				
	Max dose of the week, µSv	Normalized dose, µSv/GBq	Max dose of the week, µSv	Normalized dose, µSv/GBq	Max dose of the week, µSv	Normalized dose, µSv/GBq
Tech1	26.04	0.16	27.11	0.84	31.24	2.13
Tech2	19.94	0.13	27.29	0.91	25.31	2.19
Tech3	11.28	0.08	20.62	0.55	12.7	0.84
Tech4	27.1	0.34	31.65	1.22	38.33	2.68

*technologists work with different activities during the week, so the table also shows the doses normalized for 1GBq activity.

It has been found, that 4th technologist, which has the shortest professional experience in the nuclear medicine department collects higher than average exposure doses. The above-mentioned dose maps, were used to identify the peaks separately. One of the peaks of the fourth operator is presented in the graph below, where a higher peak can be seen from 10:28 a.m. to 10.38 a.m. (Fig. 25), when a more severe patient needed help, moreover, the higher accumulated dose per day was captured due to a bigger number of patients, than usual. The dose of 14.36 µSv was the highest registered accumulated dose throughout the whole research period. While the doses of the other technologists did not exceed more than 6 µSv, ~9 µSv and 7.6 µSv for first, second, and third technologists, respectively. The maximum dose of the fourth technologist is almost twice higher, comparing with others. Possible assumption, would be that the shortest working experience of three years, as mentioned above. As published in *Medical Physics in the Baltic States 15 (2021)* conference book, the analysis of average accumulated dose per day, leads to the suggestion that fourth technologist has a tendency of collecting higher doses in comparison with colleagues. He was provided with a recommendation to acquire additional practical training [75].

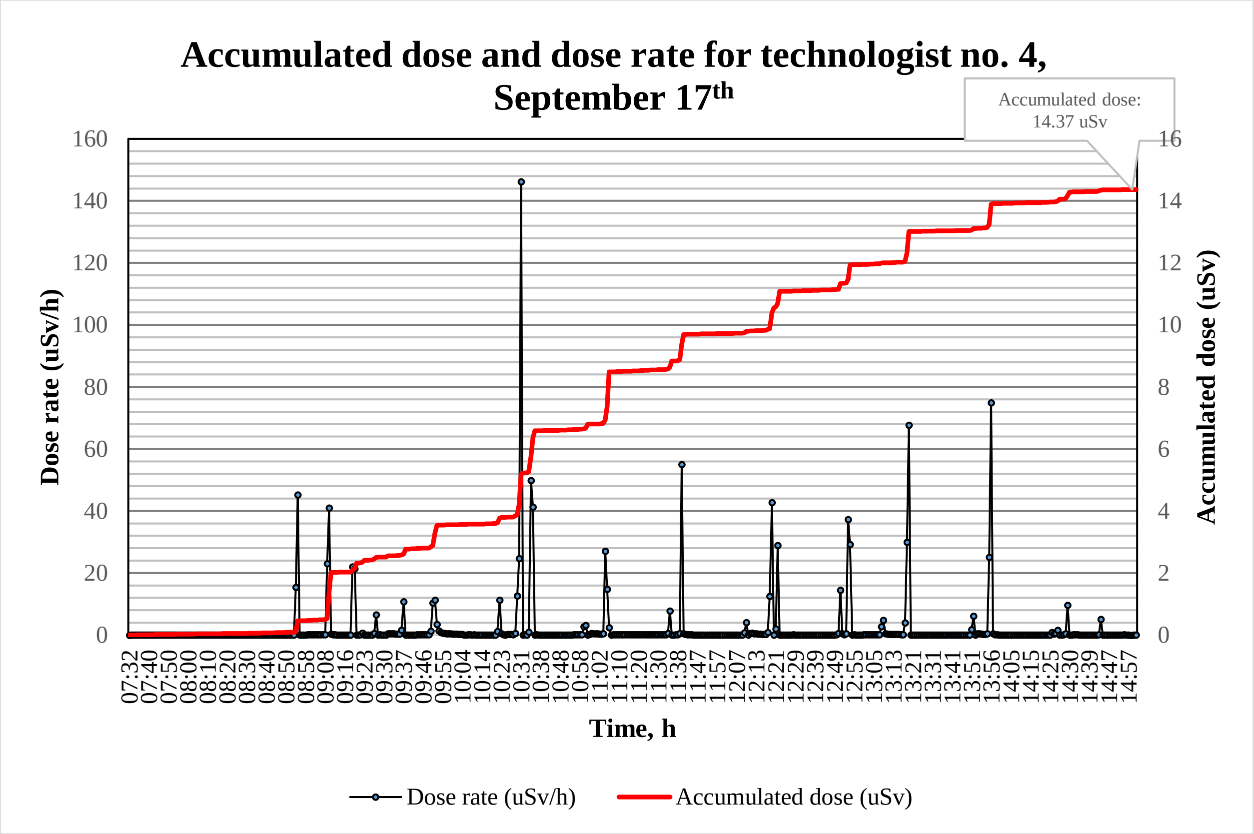


Fig. 25. Accumulated dose and dose rate graph (technologist no. 1)

The graph from the working day of the first technologist represents the peak from 1:20 p.m. till 1:37 p.m., which can be seen in Fig. 26, when operator had to help a patient to get on and off the table. After analysing the graphs and finding the causes of the higher accumulated doses than usual average, it can be assumed that the whole-body dosages throughout the working day are not collected during preparation of the radiopharmaceuticals. During this research, the analysed higher whole-body dose peaks were registered when technologists spend more time with the patients than regularly, or came in close contact with them, while helping or observing their condition during, or after the procedure, especially in the procedures with cardiac patients.

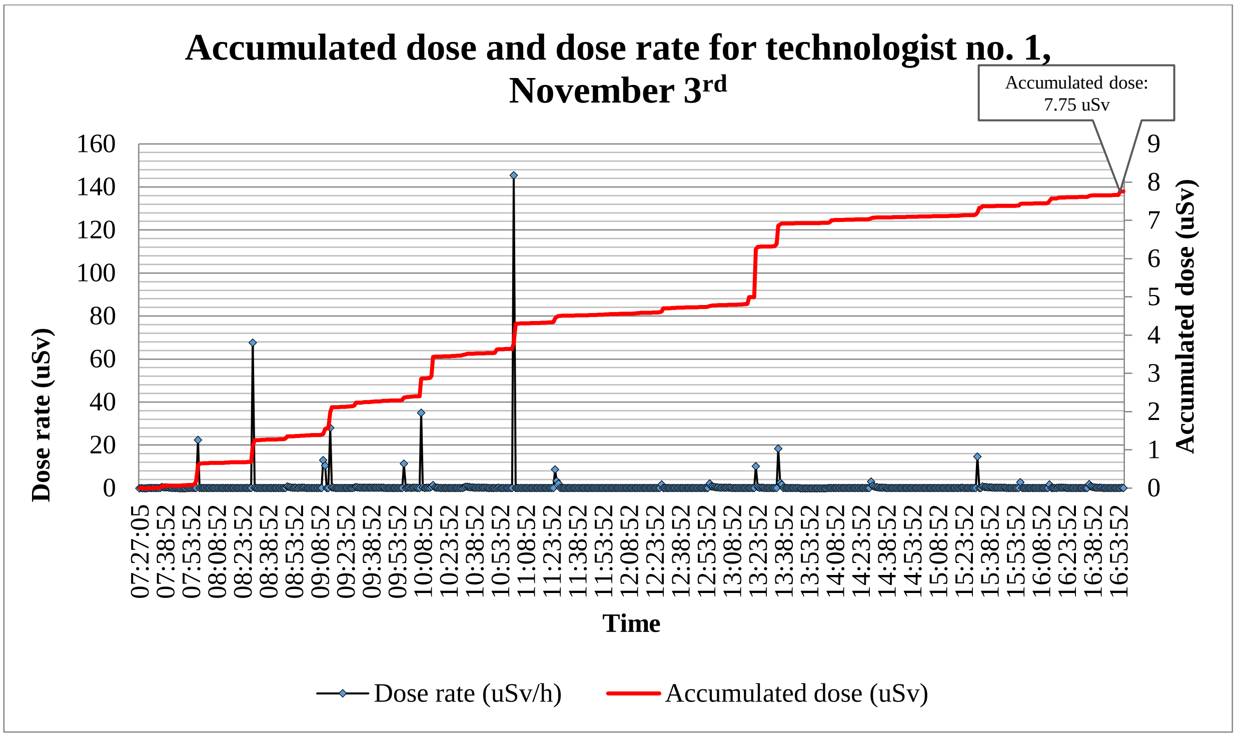


Fig. 26. Accumulated dose and dose rate graph (technologist no. 3)

3.2. Doses to the fingertips

Fingertip doses were measured on several days, when technologists were performing different tasks and manipulating two separate radiopharmaceuticals, as well as working in different places of Radiology department. The fingertip doses were measured and analysed for three technologists. For two of them, fingertip dose results were compared with a ring dosimeter measurement.

Besides monitoring the whole-body exposure, doses to the fingertips were measured, in different working positions, which were divided by the working days, as technologists are working according to a schedule. First day to third day, when fingertip doses were collected, 4th technologist, was working in the ^{99m}Tc hot-lab and was preparing and pre-filling radiopharmaceuticals, also, performed injections of solutions to the patients. The maximum dose value was registered for a middle finger of the right hand – 6.85 mSv (Fig. 27) and a middle finger of the left hand – 6.37 mSv. The biggest dose computed dose with a ring dosimeter – 1.97 mSv, which is almost 3.5 times lower in comparison with highest dose of the fingertip. On days from 4 to 6, the operator was injecting the ^{99m}Tc labelled solutions to the patients (a very few patients in comparison with other days). Highest dose registered on these days was on a middle finger of the right hand – 4.35 mSv, and similar dose registered on the same day was on the left thumb – 4.33 mSv. The highest dose carried out from a ring dosimeter – 1.11 mSv, which is almost 4 times lower than dose to the fingertip. As can be seen from the graph, the most exposed fingers are the middle fingers of the both hands, and left thumb. Thus, the technologist should be wearing a ring dosimeter on a middle finger of the right hand, though while performing this research, the dosimeter was worn on a ring-finger, which was chosen by a personal preference.

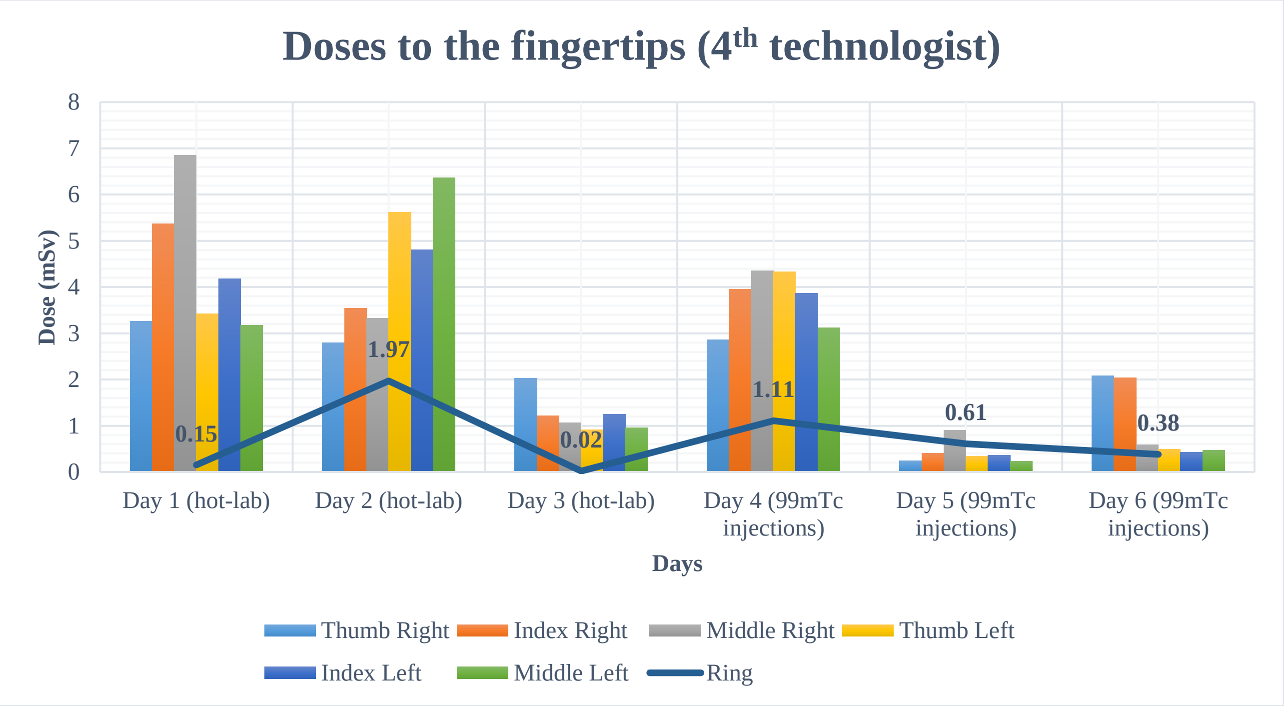


Fig. 27. Recorded fingertip doses of the fourth technologist

First nuclear medicine technologist, was giving FDG (^{18}F) injections to the patients on first three days, of the measurements. Maximum doses were registered on a middle finger of the left hand – 1.27 mSv and the right thumb, which was 1.11 mSv (Fig. 28). Highest dose registered with a TLD ring dosimeter on these days were – 0.25 mSv, which is more than 5 times lower in comparison with the maximum dose value of the fingertip. On the last two measurement days (4 – 6), the technologist was operating in the ^{99m}Tc hot laboratory with preparation of the eluates, moreover, he was pre-filling syringes with the solution. Maximum registered dose was – 0.87 mSv for a middle finger of the left hand, while the biggest value registered with a ring dosimeter – 0.44 mSv, which is almost two times lower in comparison with the dose of a fingertip. After analysing the measurements, the technologist should be recommended to wear ring dosimeter on a middle finger of the left hand, which is the most exposed, as can be seen from the graph. While performing this research, the TLD ring was worn on an index finger, by personal selection. As can be assumed from these results, injections of different radiopharmaceuticals, ^{18}F FDG or ^{99m}Tc eluate, did not affect dose divergence of the fingertip exposure.

Comparing the doses of the fingertips when performing FDG injections, the doses of the first technologist are lower than some reported in the literature. As reported by *Wrzesień et. al.* in the research performed in Poland hospital, which was published in 2018, the nuclear medicine technologist collected the maximum $H_p(0.07)$ dose of 4.26 mSv, while the minimum value was 0.16 mSv, when performing ^{18}F FDG injections to the patients [76]. The reported dose is more than three times higher in comparison with the maximum dose of the first technologist when working with the injections of the same radiopharmaceutical, in this research. Moreover, the fully automated preparation process of ^{18}F FDG is great optimization of radiation protection of the staff, in comparison with manual labelling of the ^{99m}Tc, which is the mean source of personnel exposure, as reported by the authors.

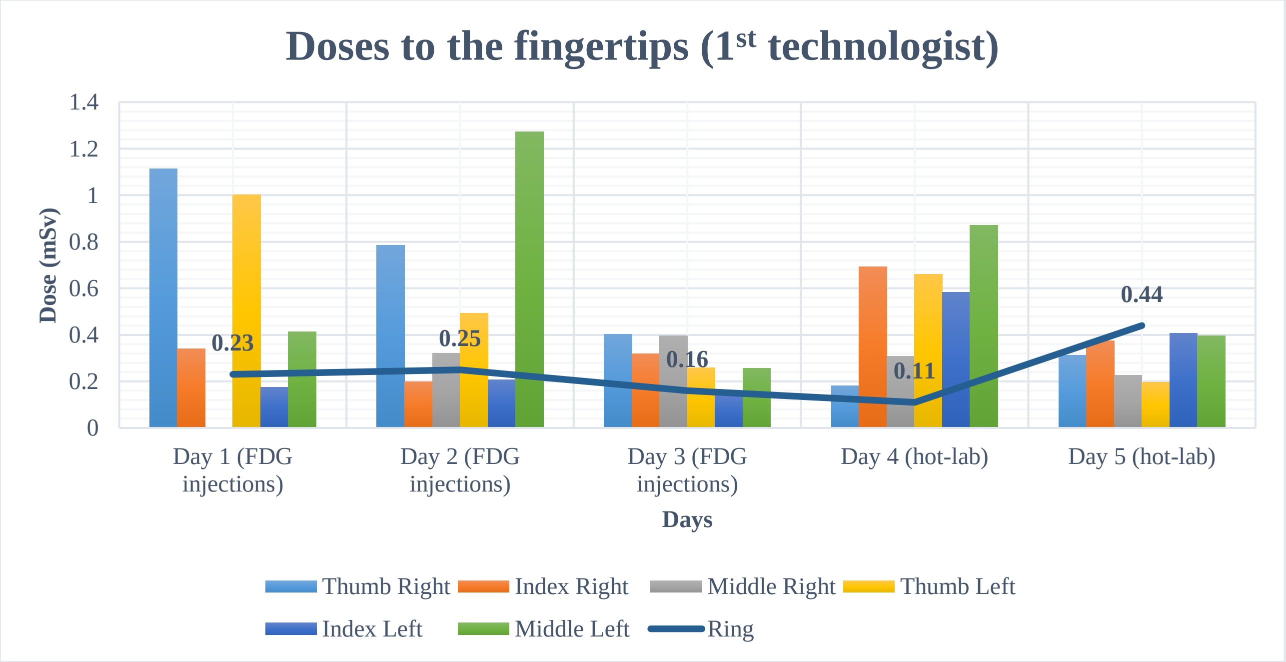


Fig. 28. Recorded fingertip doses of the first technologist

On the first day of the fingertip dose measurements 3rd operator was working with the preparation of the ^{99m}Tc radiopharmaceuticals and was pre-filling the syringes in the hot-lab. The highest dose was registered on the middle finger of the right hand – 14.44 mSv, second largest dose – 8.88 mSv – on a thumb of the right hand (Fig. 28). On the second day, the technologist was administering ^{18}F injections to the patients. The highest dose – 4.36 mSv, once more collected on the middle finger of the right hand. While performing these measurements, the third technologist was not wearing a ring dosimeter, so the doses cannot be compared, though after analysis of the results, the recommendation would be to wear a ring dosimeter on a middle finger of the right hand, which collected the highest dose.

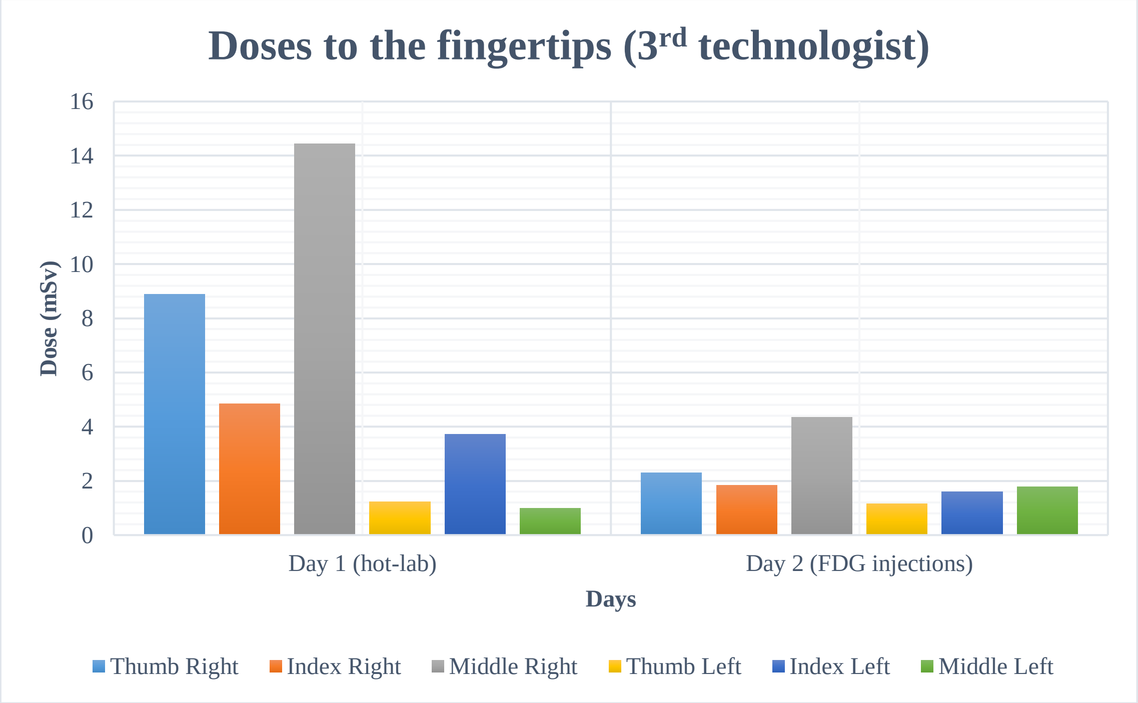


Fig. 29. Recorded fingertip doses of the third technologist

The study confirmed the hypothesis that the exposure of different fingers depends on the individual skills and habits of the NM technologist, therefore, wearing a TLD ring in a strictly defined place for everyone, cannot be applied, who are working in the nuclear medicine field. Nevertheless, the individual guidance on the position of the dosimeter should be provided. The results show that, the personnel get highest hand exposure, when they are working in a ^{99m}Tc hot-lab, which can be up to ten times higher, than the dose collected by the fingertips when performing tasks in an operating room, due to the use of automatic injectors during the procedure of the injection.

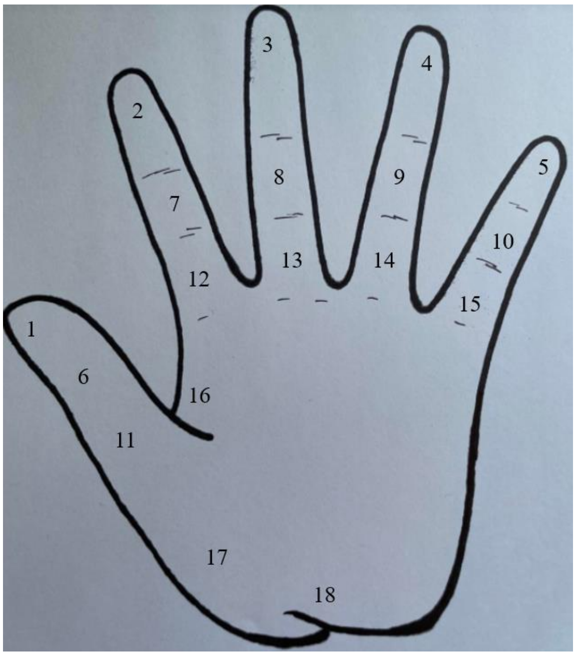
Hand exposure is usually uneven, so daily methods of monitoring worker exposure using TLD rings or wrist dosimeters are not a sufficient tool to assess worker exposure, especially as doses to the fingertips may exceed the annual dose limit of 500 mSv to the extremities, mostly when working with the preparation of ^{99m}Tc in a hot laboratory. If finger dosimetry is not performed, ICRP recommendation is used for multiplying the obtained dose value, from a ring dosimeter by a factor 6, in order to assess doses of the fingers. Unfortunately, this number may differ significantly from the actual exposure of the fingers, as showed the results of this research. Moreover, research has showed that, the earlier on, published recommendation by ORAMED to wear a ring dosimeter on an index finger is not suitable, and individual dosimetry must be performed [6].

The use of a multiplier of 6 in the conversion of fingertip doses to a value obtained by a TLD ring was partially confirmed by analysing the maximum finger exposure doses accumulated in the ^{99m}Tc hot-lab, when technologists were preparing radiopharmaceuticals, though the exposure values of the ring dosimeter were close to fingertip doses, when technologists were operating in other working places.

3.3. Dose measurements with a hand phantom

Artificial hand was used for additional measurements, in order to determine the most exposed part of the hand, as well as, to find out the differences between doses obtained at the fingertips and base at the fingers. Once again, the assessment was performed in ^{99m}Tc hot-lab in Radiology department of Kaunas Clinics. The syringe, which was pre-filled with ^{99m}Tc radiopharmaceutical and was held for 25 seconds to simulate the injection of the radiopharmaceutical into the syringe. The activity during the experiment was 1.16 GBq. Eighteen TLDs were placed on the fingers and the palm of the hand (the positions can be seen on Table 6).

Table 6. Positions of the TLDs and measured dose

TLD positions	Number	TLD place	Dose, mSv/GBq
	1	tip of the thumb	1.71
	2	tip of the index finger	6.27
	3	tip of the middle finger	0.33
	4	tip of the ring finger	0.29
	5	tip of the little finger	0.97
	6	middle phalanx of the thumb	0.60
	7	middle phalanx of the index finger	14.15
	8	middle phalanx of the middle finger	0.52
	9	middle phalanx of the ring finger	2.80
	10	middle phalanx of the little finger	0.64
	11	proximal phalanx of the thumb	1.31
	12	proximal phalanx of the index finger	0.94
	13	proximal phalanx of the middle finger	1.71
	14	proximal phalanx of the ring finger	0.04
	15	proximal phalanx of the little finger	1.66
	16	trapezoid	0.80
	17	base of the thumb (trapsium)	1.01
	18	palm	0.95

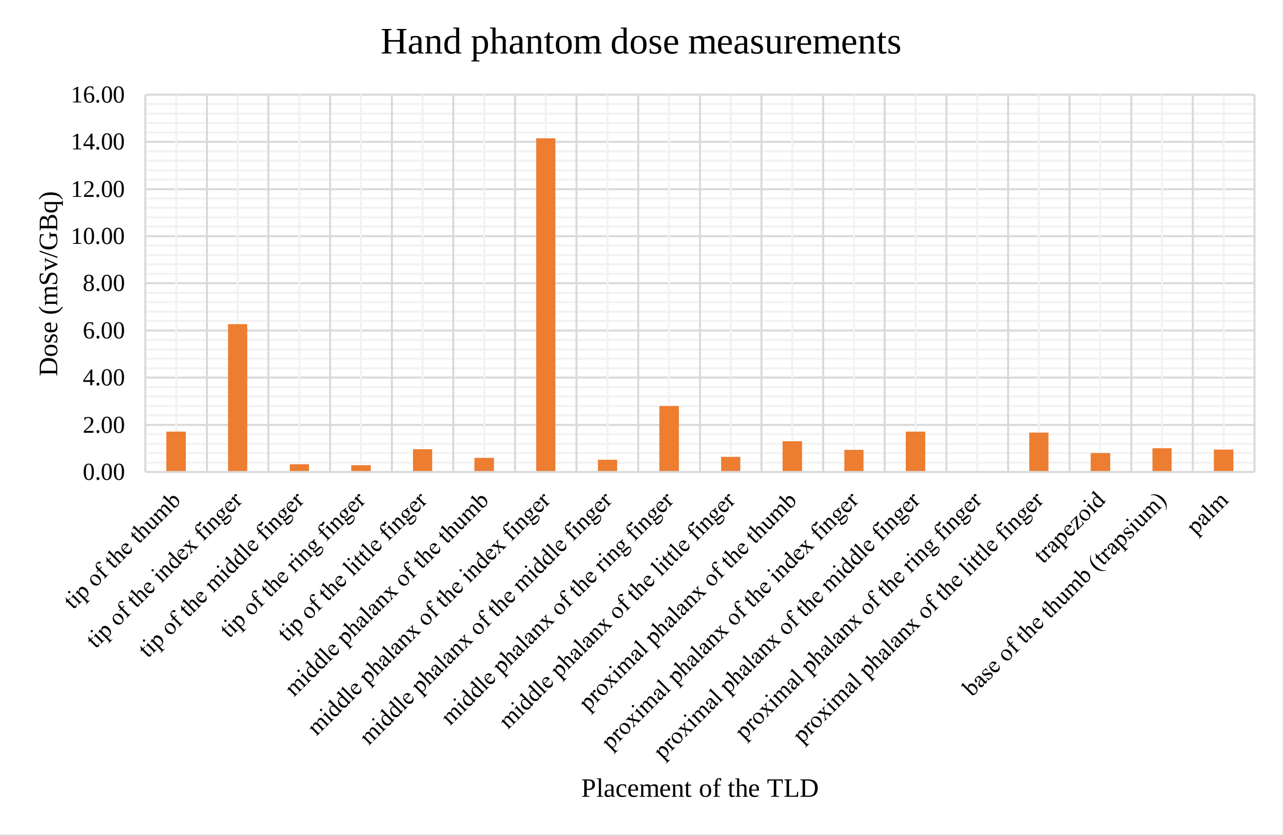


Fig. 30. Average dose distribution of the artificial hand measurements

As can be seen from the graph the most exposed part of the artificial hand measurements is middle phalanx of the index finger, which collected 14.15 mSv (position no. 7) and tip of the index finger – 6.27 mSv (position no. 2). At the base of the index finger, where the ring dosimeter would take place, the dose registered was 0.94 mSv (position no. 12), which is 15 times lower, than the most exposed part of the finger (middle phalanx, TLD no. 7). The dose difference between the tip and the base of the finger (where ring dosimeter would be worn) are 1.3, 6.67, 8.5 times lower, for thumb, index and ring finger, respectively. Contrastingly, for middle and little finger, doses recorded at the base were higher than on the tip (5.077 and 1.72 times, respectively). The difference between the most exposed part of the hand and the smallest dose obtained from the ring dosimeter place is a few hundred times (between positions no. 14 and no. 7).

It is useful to mention, that the experiment conditions do not correspond to actual ^{99m}Tc radiopharmaceutical preparation procedure done by the technologists, e.g. syringe shielding was not in place during the modelling, due to that the doses are higher than registered in a working day by operators. However, hand modelling was chosen to monitor and to see the tendencies of the distribution of the dose throughout the whole palm, which is usually not possible with a technologist, due to the inconvenience when working with many TLD dosimeters.

According to the study, published in *Physica Medica,* the tip of the index finger receives the highest dose, which supports the results, obtained with the hand phantom measurements, that the index finger is the most exposed. The mean dose equivalent value for this finger was – 38.5 μSv/GBq. Moreover, the authors calculated the possible yearly dose, based on the daily handled activities and working days, which resulted to a number, which would exceed the limit of the 500 mSv, therefore, proving the concerns of many researchers [77]. *Kollaard et. al.* confirms the proposal, of index finger being the most exposed to radiation. It is said, that the tip of the index finger of the ND hand, gets higher doses, with the best correlation with the dose taken from the ring dosimeter of the same finger [17]. In addition to these results, ORAMED publication proves that the tip of the index finger of the non-dominant hand is the most exposed during the preparation of the ^{99m}Tc radiopharmaceuticals, ICRP, on the other hand, states that the fingers of the dominant hand are the most exposed, based on a comprehensive literature study [6, 78]. *Carnicer et al.* and *Wrzesien et al.,* outlined that wrist doses usually are on average 20 – 25 times lower than the maximal dose of the fingertips, though ring doses generally are five times lower. This led to the ORAMED guidance that wrist dosimeters should be avoided in NM due to the lowest correlation and greatest likelihood of underestimation [79, 80]. It should be emphasized that the published articles contain a wide range of data in terms of dosimeter location and their number, amount of monitored personnel and different operations, manipulation type, and use of shielding.

Conclusions

1. It was found that the doses to the fingertips were dependent on the experience of the individual and his/her working habits. The results have shown that the technologist with the shortest working experience collected higher whole-body exposure doses than the others with a yearly average whole-body $H_p(10)$ dose of 0.93 mSv. Highest accumulated dose of the technologist during a single working day was 14.36 μSv. Highest accumulated doses during one day did not exceed 6 μSv, ~9 μSv and 7.6 μSv for first, second, and third technologists respectively.
2. It was found that the whole-body doses accumulated when working in a hot laboratory (with the highest registered $H_p(10)$ dose of 0.34 μSv/GBq) was lower in comparison with the doses, accumulated when working with the injections of the radiopharmaceuticals (with the highest $H_p(10)$ dose of 2.68 μSv/GBq).
3. Based on the results, maximum doses to the fingertips of the third and fourth technologist were determined for the middle finger of the right hand (14.44 mSv and 6.85 mSv, respectively) and for the middle finger of the left hand for the first technologist (1.27 mSv).
4. Dose measurements performed using artificial hand showed that the most exposed part of the hand during manipulation of ^{99m}Tc injection into a syringe was middle phalanx of the index finger (14.15 mSv) and a tip of the index finger (6.27 mSv). The dose of the most exposed part of the hand (index finger) was 15 times higher as compared to the dose measured at the base of the finger (0.94 mSv). The simulation using artificial hand allowed for observing dose distribution across the hand area. The underestimation of the highest dose to fingers based on recalculation from ring dosimeter measurement, indicated that the fingertip dose estimation by multiplying dose at the ring place by a factor of 6 (which is recommended by international authorities) is incorrect, and cannot be applicable for monitoring. Artificial hand measurements showed, that the 500 mSv limit, can be easily surpassed, especially if the doses are calculated properly.

Recommendation: Individual hand dose monitoring should be performed at least once per year. This is absolutely necessary, in order to determine the most exposed finger, which in turn will be chosen as a place for the dosimetry ring and evaluation of the doses. This recommendation is in line with a recent regulation No. V-91 issued by Radiation Protection Center on 29th December, 2020, which recommends wearing ring dosimeters on the fingers, that are mostly exposed.

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