Kaunas University of Technology

Faculty of Mathematics and Natural Sciences

Evaluation of Hand Exposure for Nuclear Medicine Staff Working with 18F- and 99mTc- Labelled Radiopharmaceuticals

Master’s Final Degree Project

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Summary

The work of nuclear medicine personnel includes preparation and injection of radiopharmaceuticals, during which hands come into close contact with the radionuclide leading to higher exposure doses to extremities. Nowadays, monitoring of hand doses of nuclear medicine personnel is performed by wearing ring dosimeter on the base of a finger of the dominant hand. However, the distribution over hand is nonuniform and the doses obtained by the ring dosimeter can be significantly lower compared to other parts, especially fingertips.

The aim of this project was to evaluate hand doses in different points for radiology technologists of the Nuclear Medicine Department of Vilnius University Hospital Santaros Klinikos working with ^{18}F- and ^{99m}Tc- labelled radiopharmaceuticals. In order to measure the doses, TLD-100 chips were used. Dosimeters were calibrated with ^{18}F and ^{99m}Tc sources in a range of (0.25-2) mSv and (0.5-4) mSv, respectively, and were read by RIALTO TLD reader. There were performed 7 measurements for personnel working in a hot lab with ^{99m}Tc, 3 measurements for injection of ^{99m}Tc- labelled radiopharmaceuticals, and 1 measurement for radiology technologist working with ^{18}F radionuclide. Overall, 15 TLD-100 positions for both hands were chosen and measured.

It was found that the right (dominant) hand received higher doses than the left (non-dominant) hand by 2.17 and 1.15 times while preparing ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals, respectively. The most exposed part working in a hot lab with ^{99m}Tc was the tip of the right thumb resulting in an average dose of 0.728 mSv/GBq, meanwhile during the work with ^{18}F, the highest dose was achieved by the tip of the right hand index finger (0.021 mSv/GBq). During the radiopharmaceutical injection (^{99m}Tc), the highest average dose was observed in the case of the left hand index finger tip (0.094 mSv/GBq) leading to 1.09 times higher average dose of the left hand compared with the right hand. During all measurements, the least exposed parts were the palm and the wrist. Also, it was determined that the maximum fingertip dose was 2.1-2.4 times higher compared with the doses from usual monitoring position. Based on the results, it is recommended to wear ring dosimeter on the base of the thumb of the dominant hand.

Andrulevičiūtė, Inga. Branduolinės medicinos personalo, dirbančio su 18F ir 99mTc ženklintais radiofarmaciniais preparatais, poveikio rankoms įvertinimas. Magistro studijų baigiamasis projektas / vadovė doc. dr. Jurgita Laurikaitienė; Kauno technologijos universitetas, Matematikos ir gamtos mokslų fakultetas.

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Reikšminiai žodžiai: branduolinė medicina, rankų apšvita, profesinė apšvita, termoliuminescencinė dozimetrija.

Kaunas, 2021. 53 p.

Santrauka

Branduolinės medicinos personalo darbas apima radiofarmacinių preparatų ruošimą ir injekavimą, kurių metu rankos turi tiesioginį sąlytį su radionuklidais, tuo pačiu apšvitinant ir darbuotojų rankas. Šiuo metu branduolinės medicinos personalo rankų dozės stebimos nešiojant žiedinį dozimetrą ant dominuojančios rankos piršto pagrindo. Vis dėlto, dozių pasiskirstymas rankose yra nevienodas, o žiedinio dozimetro dozių parodymai gali būti ženkliai mažesni palyginti su kitomis dalimis, ypač pirštų galiukais.

Baigiamojo projekto tikslas – įvertinti rankų dozes skirtinguose taškuose Vilniaus universiteto ligoninės Santaros klinikų Branduolinės medicinos skyriaus radiologijos technologams, dirbantiems su ^{18}F ir ^{99m}Tc ženklintais radiofarmaciniais preparatais. Dozėms matuoti buvo naudojami TLD-100 dozimetrai. Jie buvo kalibruoti naudojant ^{18}F ir ^{99m}Tc šaltinius atitinkamai (0,25-2) mSv ir (0,5-4) mSv diapazone bei nuskaityti RIALTO TLD skaitytuvu. Buvo atlikti 7 matavimai personalui, dirbančiam „karštoje laboratorijoje“ su ^{99m}Tc, 3 matavimai injekuojant ^{99m}Tc žymėtus radiofarmacinius preparatus ir 1 matavimas radiologijos technologui, dirbančiam su ^{18}F radionuklidu. Iš viso buvo pasirinkta ir išmatuota 15 TLD-100 pozicijų abejoms rankoms.

Nustatyta, kad ruošiant ^{99m}Tc ir ^{18}F ženklintus radiofarmacinius preparatus dešinė (dominuojanti) ranka gavo 2,17 ir 1,15 kartų didesnes dozes palyginti su kaire (nedominuojančia) ranka. Labiausiai apšvitinama rankos dalis dirbant „karštoje laboratorijoje“ su ^{99m}Tc buvo dešiniojo nykščio galiukas (vidutinė dozė buvo 0,728 mSv/GBq), tuo tarpu dirbant su ^{18}F, didžiausia dozė buvo nustatyta dešiniojo rodomojo piršto galiuke (0,021 mSv/GBq). ^{99m}Tc ženklintų radiofarmacinių preparatų injekcijų metu didžiausia vidutinė dozė buvo nustatyta kairiojo rodomojo piršto galiuke (0,094 mSv/GBq), todėl vidutinė kairės rankos dozė buvo 1,09 karto didesnė palyginti su dešine ranka. Atliekant matavimus, nustatyta, kad mažiausiai apšvitintos buvo delno ir riešo dalys. Be to, buvo įvertinta, kad didžiausia piršto galiuko dozė buvo didesnė 2,1–2,4 kartus palyginti su įprastos rankų žiedinio dozimetro padėties rezultatais. Remiantis gautais rezultatais, rekomenduojama žiedinį dozimetrą dėvėti ant dominuojančios rankos nykščio pagrindo.

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Abbreviations:

APD – active personal dosimeters;

CB – conduction band;

ECC – element correction coefficient;

IAEA – International Atomic Energy Agency;

ICRP – International Commission on Radiological Protection;

LAR – lifetime cancer risk;

NM – nuclear medicine;

OD – optical density;

OSLD – optically stimulated luminescent dosimeter;

PET – positron emission tomography;

RPC – Radiation Protection Centre;

RPLD – radio-photoluminescent dosimeter;

SPECT – single photon emission tomography;

TLD – thermoluminescent dosimeter;

VB – valence band.

Introduction

With a rapid development of medical technology, the nuclear medicine (NM) sector has grown significantly, so as increased the number of NM procedures performed each year. NM personnel are one of the most occupationally exposed medical groups worldwide as they have to work directly with open radioactive sources, the activity of which can vary from a few tens to thousands of MBq per procedure [1].

The *problem* is increasing number of procedures, due to this reason radiation safety of personnel has become a very *important* and *relevant* topic. Even if precautions (e.g. shielding) have been implemented into NM departments, due to higher amount of patients, the radionuclide activity that the personnel has to deal with is also higher and might lead to higher annual doses. NM personnel is exposed to chronic low-dose radiation which leads to an increased risk of thyroid and blood cancer [1-2]. Also, female workers have a higher lifetime cancer risk (LAR) of breast cancer [1]. According to studies, the greatest radiation doses in NM field are obtained by radiology technologists [1-2].

In NM, hands are the most exposed part of NM workers since the radioactive source is very close to hands while preparing and administering radiopharmaceuticals to patients. To evaluate hand exposure, NM staff usually wear ring dosimeter on the base of a finger of the dominant hand, however, published studies show [2–5] that the dose distribution over the hand is inhomogeneous and can be significantly different. The main *problem* of evaluating accurate extremity doses arise from the fact that fingertips are the most exposed part of the hands and there is a chance that the worker can exceed 500 mSv/year equivalent dose limit.

The aim is to evaluate hand exposure for nuclear medicine staff working with ^{18}F- and ^{99m}Tc- labelled radiopharmaceuticals.

The tasks:

1. To analyse dose distribution over hands for nuclear medicine personnel working with ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals.
2. To analyse and compare average hand doses of nuclear medicine personnel received during preparation and administration of ^{99m}Tc- and preparation of ^{18}F- labelled radiopharmaceuticals.
3. To compare exposure doses from ring dosimeter position with other measured points.
4. To determine the most appropriate location of the dosimeter in the hand for periodic dosimetry.

1. Literature review

1.1. Nuclear medicine

Nuclear medicine is the field of medicine that uses unsealed sources of radiation (radionuclides) for diagnosis and therapy [6]. In this field, diagnosis of a disease is based on the functionality of tissue or organs, meanwhile, the radiological procedures (X-ray, computed tomography) are commonly based on structural appearance.

Diagnostic nuclear medicine uses radiopharmaceuticals – radioactive tracers which are a combination of a gamma-ray emitting or positron-emitting radionuclide and a biologically active molecule/drug [2]. Radioactive tracers are short-lived isotopes (e.g., ^{99m}Tc, ^{18}F) connected to chemical compounds which permit particular physiological processes to be investigated and are introduced into the patient body by inhalation, injection or orally [8]. A decaying radionuclide emits gamma-rays or high-energy photons. An external detector, which is called a gamma camera, detects the gamma-rays/photons, and forms an image of the distribution of radioisotope accumulated in that tissue or organ [9].

There are distinguished two broad classes of NM imaging, namely, PET (positron emission tomography) and SPECT (single photon emission computed tomography) [9]. SPECT imaging uses gamma cameras to produce 3-dimensional images of the gamma-ray emitting radioactive tracers. The main advantage of this technique is the ability to assess tissue functionality and physiology [10]. Another method, PET, uses radionuclides that emit a positron which rapidly annihilates with surrounding electrons resulting in the simultaneous emission of two identifiable high-energy gamma photons moving in opposite directions. PET images are formed with detectors rotating around the patient and collecting data about photon distribution [9].

1.2. Occupational exposure of nuclear medicine workers

Nuclear medicine workers are occupationally exposed to ionising radiation on a daily basis as a part of their job. Personnel is exposed to ionising radiation while preparing radiopharmaceuticals, injecting them to patients, and supervising the patient during image acquisition [11]. Working with open radioactive sources causes not only external exposure to staff but also internal exposure followed by inhalation or ingestion of radioactive materials [12].

Article 3 [13] of the Radiation Protection Convention (C115) organized by International Labour Organization states that “in the light of knowledge available at the time, all appropriate steps shall be taken to ensure effective protection of workers, as regards their health and safety, against ionising radiations”. Protection of NM workers is based on the ALARA principle (as low as reasonably achievable) meaning that even if the worker is occupationally exposed to ionising radiation, all reasonable methods should be employed to make the dose as low as possible [14].

Occupational monitoring and safety requirements of NM personnel in Lithuania are regulated by Lithuanian Hygiene Standards HN 77:2015 “Radiation Protection and Safety in Practice of Nuclear Medicine”, HN 73:2018 “Basic Standard on Radiation Protection” and HN 112:2001 “Requirements for monitoring of internal exposure”, and “Law on radiation protection”. Radiation Protection Centre (RPC) is the institution which is responsible for the assessment of internal and external occupational doses. According to RPC, nuclear medicine workers are one of the most occupationally exposed medical groups. The average annual effective dose for NM personnel in 2019 was 0.43 mSv while the doses for radiotherapy, dentistry, X-ray diagnostic and computed tomography workers were 1.95, 2.69, 2.04, 2.53 times lower and resulted in 0.22, 0.16, 0.21 and 0.17 mSv occupational dose, respectively [15].

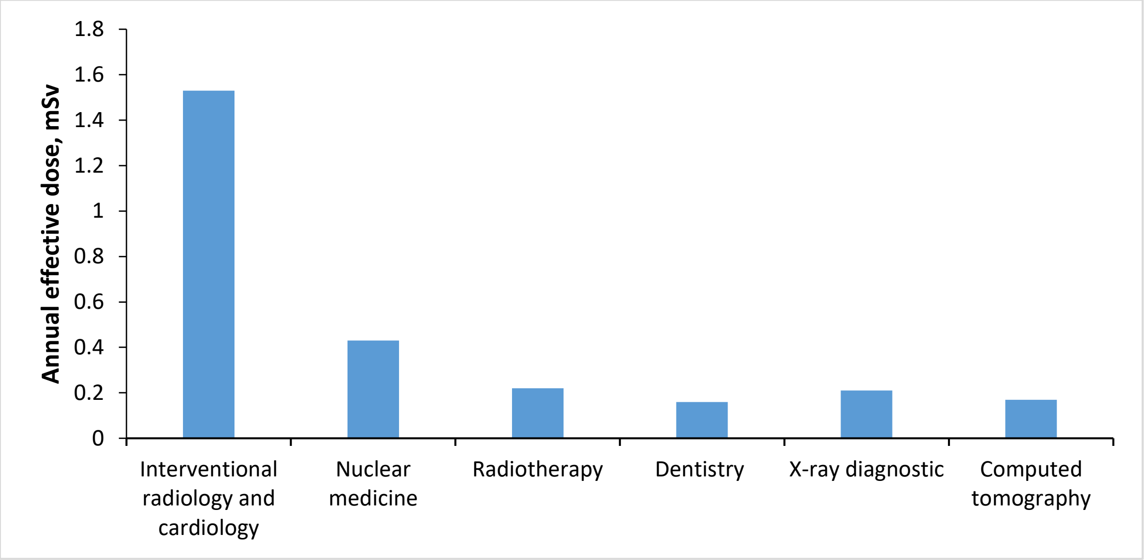


Fig. 1. Annual effective doses for medical workers in 2019 [15]

1.2.1. Dose limits

Thanks to occupational dose limits, it is possible to make sure that no worker is subject to exposure of unacceptable radiation amount in planned situations. According to International Atomic Energy Agency (IAEA), the recommended dose limits for medical personnel over the age of 18 years are [16]:

- An effective dose of 20 mSv/year averaged over 5 years in a row with no single year being higher than 50 mSv.
- An equivalent dose to the eye lens of 20 mSv/year averaged over 5 years in a row with no single year being higher than 50 mSv.
- An equivalent dose to the extremities and skin – 500 mSv/year.

The dose limits for 16–18-year-old students who use radioactive sources for their study practice are stricter; they are as follows [16]:

- An effective dose of 6 mSv/year.
- An equivalent dose to the extremities and skin – 150 mSv/year.
- An equivalent dose to eye lens of 20 mSv/year.

If a woman who works in controlled areas or supervised areas is breast-feeding, pregnant, or suspects her pregnancy, she must notify her employer about it as soon as possible. The worker should take into consideration the working conditions in nuclear medicine department and adapt them in such a way so that the embryo/foetus would be protected as much as required for people of the public. These limits are:

- An effective dose of 1mSv/year.
- An equivalent dose to the skin – 50 mSv/year, to the eye lens – 15 mSv/year [16].

1.2.2. External dose assessment

External radiation doses for NM staff are usually measured by using personal dosimeters. Individual monitoring is important to show that no worker has exceeded any dose limit and to confirm the adequacy of workplace monitoring [17]. IAEA claims that individual monitoring is required the most for radiology technicians, NM physicians, radiopharmacists, nurses, and those who prepare, dispense and administer radiopharmaceuticals to patients [18].

There are two main types of dosimeters used for the assessment of occupational exposure, namely, passive and active dosimeters. Passive dosimeters are those that must undergo a certain reading process before obtaining the dose result and provide an overall cumulated dose, while active dosimeters show the dose received by the worker instantly [19].

Thermoluminescent (TL), optically stimulated luminescent (OSL), radio-photoluminescent (RPL) and film badge dosimeters are passive dosimeters that are used for personal dosimetry most often. TLDs, OSLDs and RPLDs are also called luminescent dosimeters as they are materials emitting a quantity of light, the intensity of which is proportional to the absorbed dose when exposed to radiation [20]. TLD and OSLD reading principle is based on light (for OSLDs) and heat (for TLDs) stimulation of sensitive crystal in the detector and monitoring the luminescence intensity with a photomultiplier tube (PMT), which is used to transform the luminescence into “counts” [21] while RPLDs consist of silver-doped glass and are subjected to UV radiation which results in the de-excitation of trapped electrons generating the luminescence [22].

All these dosimeters have their own advantages and disadvantages. The main problem of TLDs is that the readout process can be done only once and there is no possibility to repeat the procedure. The luminescent centres that were created when irradiated disappear after the TLDs are heated, meanwhile RPLs do not eliminate the luminescent centres and allow to re-readout them again [23]. The advantage of TLDs is that they are of high sensitivity, accurate, the readout procedure is quite simple, OSLs have stable sensitivity, high speed of readout, luminescence efficiency and are precise and accurate [24]. Moreover, TLDs are preferable for extremity monitoring, more detailed information about the different TLD materials and their principles are described in subchapter 1.3.

A. H. Benali et al. [23] compared 3 luminescence detectors, namely, TL dosimeter LiF:Mg, Ti (TLD-100), OSL dosimeter Al_2O_3:C and RPL glass dosimeter GD-301. Monte Carlo simulations were used to determine the dosimetric properties of these detectors. The main characteristics of dosimeters used in this study are provided in Table 1.

Table 1. Characteristics of luminescent detectors [23]

	RPL-GD-301	**TLD-100 (LiF:Mg, Ti)**	**OSLD (Al_2O_3:C)**
Diameter, mm	1.5	-	1.5
Length, mm	8.5	3x3x1 mm^3	8.5
Elemental composition, %	P: 31.55, O: 51.16, Na: 11.00, Al: 6.12, Ag: 0.17	Li: 26.72, F: 73.259, Mg: 0.02, Ti: 0.001	Al: 52.92, O: 47.07, C: 0.010
Effective atomic number Z_{eff}	12.04	8.3	11.14
Density, g/cm^3	2.60	2.64	3.98

It was found that the absorbed dose mainly depends on the field size due to Z_{eff} of material. The RPLG and OSL dosimeters were attenuating the medium more than TLDs and their Z_{eff} values were 1.45 and 1.34 times higher, respectively, also probability of photoelectric effect to occur increases with increased ratio of Z elements [23]. Monte Carlo simulated dose-to-water energy response results when the materials were exposed with megavoltage X-ray beam showed that the energy dependence for OSL and RPGL dosimeters was lower than 2.2% and for TLD dosimeters it was lower than 5.8% [23].

Another type of dosimeters used for personal dosimetry is film badges. These dosimeters consist of two main parts: a photographic film and a holder that contains certain radiation attenuating filters. Films are made of silver bromide (AgBr) crystals and are suspended in a gelatinous matrix and are not tissue equivalent. On a plastic foundation, a small layer of this emulsion is evenly applied. A latent image is produced when ionizing radiation interacts with the grains in the emulsion. The silver ions become darker in subsequent development. The OD is measured with a densitometer, and the exposure dose is calculated. These dosimeters are not expensive and they are very reliable, however, they are one-time use only and cannot be reused [25].

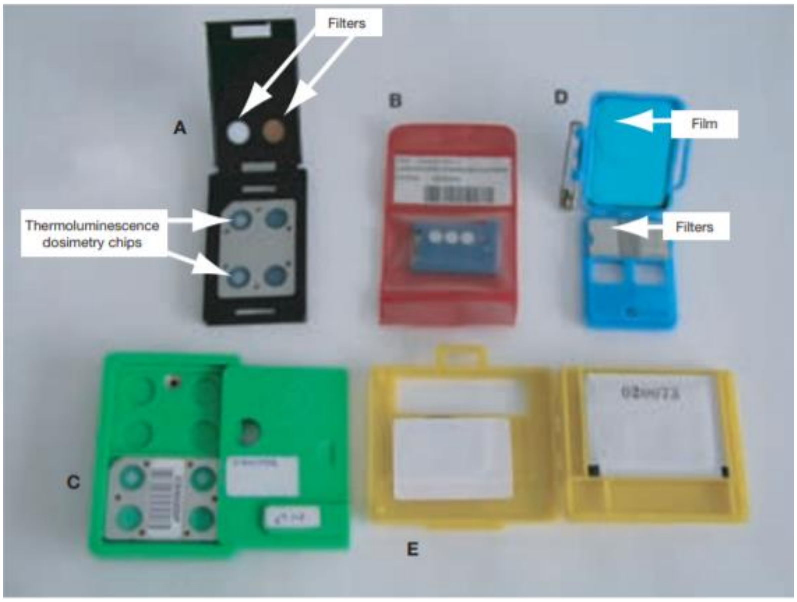


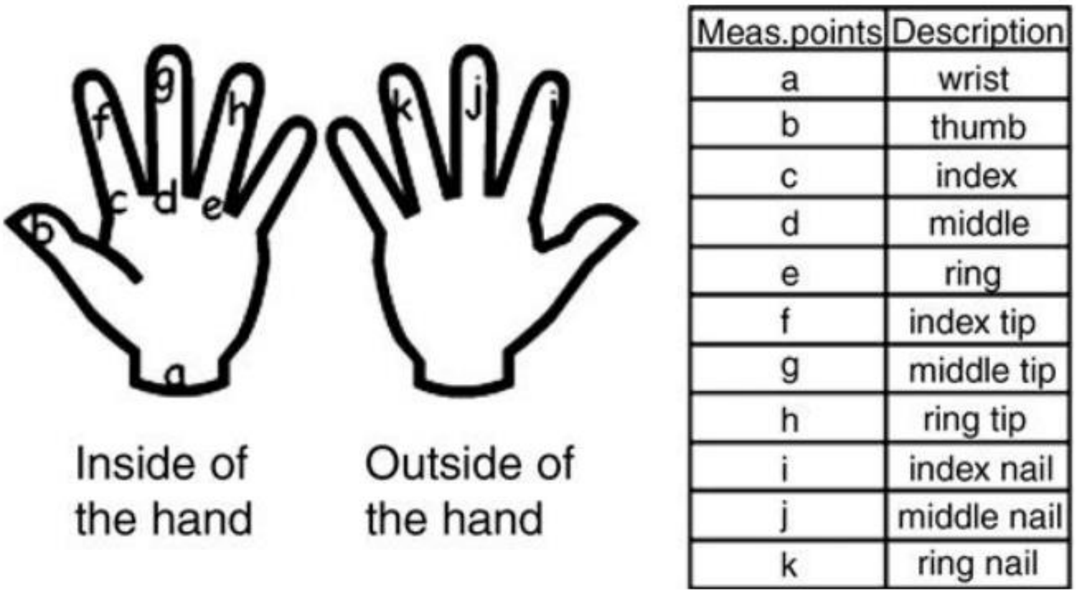
Fig. 2. Example of TL dosimetry (A, B, C) and film badges (D, E) [26]

Active personal dosimeters (APDs) are used for day-to-day monitoring. They are compact, lightweight instruments that are powered by electrical circuity (mainly a battery) and show dose or dose rate immediately [27]. While hospitals choose passive dosimetry as the main individual monitoring technique, APDs are also being used in hospitals increasingly. Usually, they are applied in nuclear medicine as secondary dosimeters since they have an alarm that soundly informs about the change in a dose rate. According to a survey by EURADOS, which collected data about the use of APDs in hospitals, the most frequently used type of APD is based on silicon diode as the detector [28].

In order to evaluate external doses, NM workers have to wear two personal dosimeters, namely, whole body ($H_p(10)$) and finger/ring dosimeter ($H_p(0.07)$). It is required that the dosimeter would be placed on the place where the exposure is expected to be the highest. ICRP recommends to wear whole body dosimeter on the front of the torso [25], meanwhile, finger dosimeter is recommended to be worn on the middle finger of the dominant hand under the gloves holding detector on the palm side [29]. Furthermore, since 1 May 2021, it has been established in Lithuania that the ring dosimeter should be worn on the most exposed hand [30].

1.2.3. Extremity (fingertip) dose assessment

Extremity dose measurements for NM staff are very important as the workers have to work with unsealed sources, prepare radiopharmaceuticals and inject them to patients, which leads to higher doses to fingers. Radiation Protection Centre announced that the average annual equivalent finger dose for NM personnel in 2019 was 21.1 mSv and the highest – 100.3 mSv [31]. However, it is assumed that the dose distribution might be significantly different over the hand, especially fingertips, and the results of ring dosimeters might be not accurate enough to evaluate if the occupational doses for staff do not exceed the recommended 500 mSv/year dose. For this purpose, the European study called ORAMED, which was performed in 32 NM departments in Europe, evaluated the most exposed parts of the hands of NM staff. In diagnostic nuclear medicine, finger dose measurements of personnel administering and preparing ^{18}F and ^{99m}Tc were selected because these radionuclides are used the most in this field. $H_p(0.07)$ was measured by high sensitivity TL (LiF:Mg:Cu:P and LiF:Mg:Ti) dosimeters. 11 different positions of each hand were chosen, TLDs were worn under the gloves. Fig. 3. shows positions of dosimeters [4].



Meas.points	Description
a	wrist
b	thumb
c	index
d	middle
e	ring
f	index tip
g	middle tip
h	ring tip
i	index nail
j	middle nail
k	ring nail

Fig. 3. TLDs positions on the hands [4]

Based on the results of ORAMED project, thumb, index tip and ring tip doses were obtained to be the highest for both dominant and non-dominant hand while preparing and administering ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals, index fingertip was the most exposed part of the hand. Also, non-dominant hand received higher doses than dominant hand. During ORAMED project, it was assumed that the dose values for finger ring might be 2-6 times lower than doses for fingertips [4].

Zoccarato et al. have also assessed fingertip doses for NM staff who prepare ^{99m}Tc radiopharmaceuticals. In this case, workers were monitored by using 4 TLD chips attached to index tip, index base and wrist of non-dominant hand and index tip of dominant hand for 2 weeks. Contrary to ORAMED findings, the highest dose was received by the index tip of the dominant hand and resulted in 63.7 µSv/GBq while the doses for index tip, base, and wrist of non-dominant hand were 38.5, 18.9, 5.4 µSv/GBq, respectively [3].

Higher doses to dominant hand were also found in Adlienė et al. study. In this study, two radiology technologists working with ^{99m}Tc were asked to wear 10 TLD chips on each hand. The average doses to the fingertips were found to be almost 2 times greater than doses to the hands. The highest doses were obtained for the right hand thumb, middle finger and index finger, doses for the left hand were a little bit lower but also resulted in higher doses for the same 3 points comparing with other doses of that hand [2].

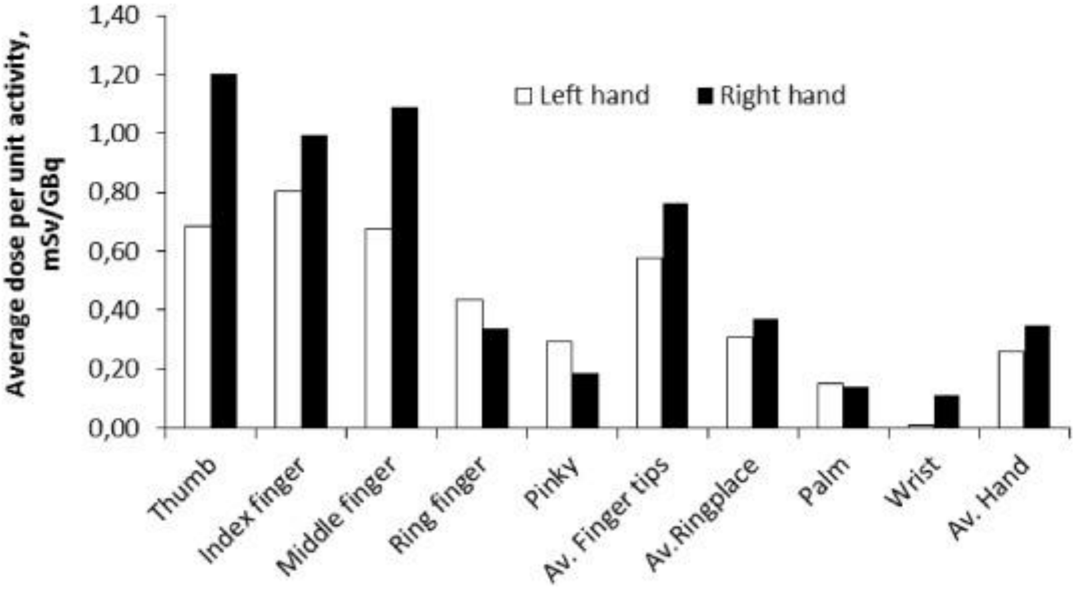


Fig. 4. Adlienė et al. study results [2]

Personnel might find it not acceptable wearing dosimeters on the fingertips for the daily extremity monitoring since they lose the sensation of touch resulting into the fact that it is more difficult to make appropriate volume adjustments of radiopharmaceuticals withdrawn into syringes. To estimate the dose of the fingertip from the results of the ring dosimeter, correction factors might be needed.

In his research, Martin reviewed different studies which report ratios of doses to the fingertip and base, and he also made a survey to evaluate the practices in the United Kingdom NM departments to find the most appropriate correction factors. It was concluded that a factor of 3 is suitable for workers who use shielding and never touch vials or needles. For personnel who use vial and syringe shielding most of the time and may touch a needle while injecting the radiopharmaceuticals to patient, a factor of 4 might be used, and for other staff who do not use any shielding in their job, a factor of 6 should be applied [32].

1.2.4. Internal dose assessment

NM workers are internally exposed by inhalation, ingestion and absorption through healthy or damaged areas of the skin. By means of monitoring occupational exposure, it is sought to guarantee that the worker would be properly protected against radiological hazards and that the protection would meet legal requirements. [33]. According to IAEA Safety Guide RS-G-1.2., occupational monitoring is recommended if committed effective doses from yearly intakes of radioactive nuclides are likely to exceed 1 mSv [25].

The main problem of internal dose assessment is that they cannot be measured directly. Doses obtained by organs and tissues are prolonged after radionuclide ingestion, resulting in the accumulation of equivalent and effective doses over time. These resulting dose quantities are called as committed effective doses ($E_{(\tau)}$) [34]. According to ICRP Publication 119, a committed effective dose is described as “the sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors (w_T), where τ is the integration time in years following the intake. The integration time is 50 years for adults and up to age 70 years for children” [35, p. 9].

Specific measures of other quantities, such as measurements of body activity (direct measurements), excretion, blood, and air saturation sampling (indirect measurement), are inferred to determine the doses obtained by personnel [33]. For initiating bioassay measurements, workplace monitoring is helpful. Furthermore, workplace characterisation can be used in conjunction with bioassay tracking because it gives valuable details about chemical and physical composition of radioactive nuclides in the workplace. ICRP distinguishes two main methods for internal dose assessment in the workplace, namely, static air sampling (SAS) and personal air sampling (PAS) [33].

PAS is a filter-based personal air sampler worn by the NM workers who are exposed. It measures concentration of activity in the area where the worker breaths. However, it is a limited technique because the airflow through the device is not the same as the workers’ breathing rate [36]. Also, results may differ considerably depending on measuring conditions such as the sampler’s orientation in relation to the source, which lapel (left or right) it is worn on, the construction of the air sampling head, particle size, etc. [33]. SAS are more used for workspace condition monitoring but could also be implemented in evaluation of concentrations in the breathing area of a worker.

Another method used to evaluate internal doses to workers is whole body/organ counting and activity measurements from bioassay samples such as faeces, blood, or urine. Direct measurements are only possible when inhaled or ingested radionuclide emits penetrating radiation (such as gamma rays) and can be detected outside the body. Detectors used for whole body or organ counting usually are placed at specific positions around the body, they are at least partially shielded to minimize interference from external sources [25]. Examples of such detectors used for individual monitoring include Ge(Li) whole body counter and Na(I) detector for thyroid activity measurements. Indirect bioassay sampling method is usually used when radionuclides do not emit penetrating radiation or emit only low energy photons. The most commonly used samples are faeces and blood [33].

To calculate committed effective doses, intake (I) value (the activity of the radioactive nuclide taken into the body) is firstly obtained by dividing measured value (M) in Bq with in vivo residual or ex vivo excretion function at time (t) [25]:

$$I = \frac{M}{m(t)} \tag{1}$$

Biokinetic models for calculating the values of m(t) have been reported by ICRP Publication 119, 134 and 137.

When the intake (I) value is known, committed effective dose ($E_{(50)}$) is calculated by Equation 2 [25]:

$$E_{(50)} = e_{ij} \cdot I \tag{2}$$

where e_{ij} is dose coefficient for route of intake i and radionuclide j.

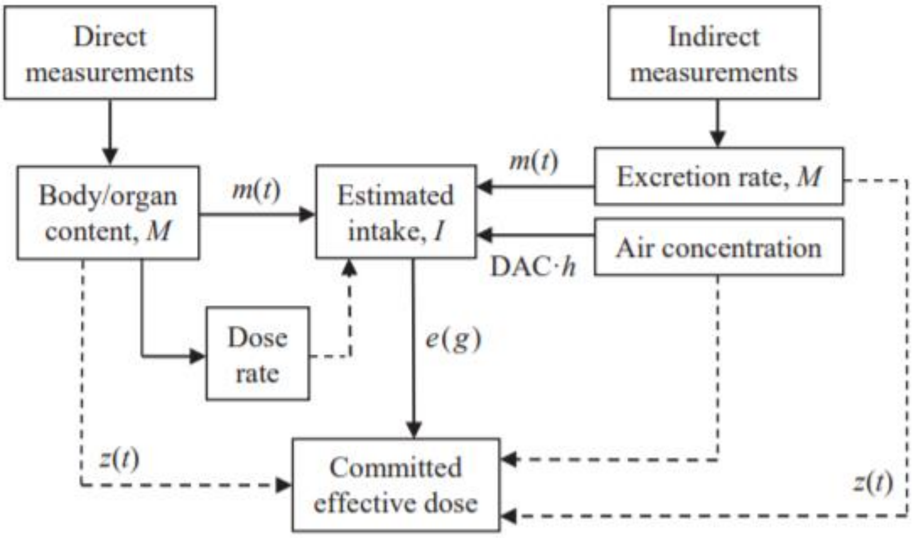


Fig. 5. Scheme of committed effective dose calculations [25]

1.2.5. Basic principles of radiation protection

To minimize the risk of stochastic effects and to prevent deterministic effects, nuclear medicine workers must comply with three main radiation protection principles in their job: time, distance and shielding.

To reduce occupational doses, time spent near the radioactive sources is very important. The longer the worker spends on preparing, injecting and positioning the patient on the scanning table, the higher dose he receives as the dose is proportional to time. For example, if the dose rate is 50 µSv/h, the worker will receive 4,2 µSv in 5 minutes and 25 µSv in 30 min.

Distance is also a very important radiation protection principle. The greater distance from the source, the lower dose is received. For example, to keep the distance while preparing (handling) radiopharmaceuticals, long tweezers might be used.

Ohiduzzaman et al. [37] investigated exposure rates at a distance from NM scans. The exposure rate for thyroid scan (average dose was 111 MBq of ^{99m}Tc-pertechnetate) after 20 min of radiopharmaceutical injection was 11.32, 6.85, 3.90 and 2.00 µSv/h when the distance was 0.25, 0.5, 1 and 2 meters, respectively. So if the NM worker would be 2 meters instead of 1 meter further from the patient, he could receive a 1.95 times lower dose. In this study, dose rate in time was also evaluated. Taking into account that the radionuclide decays, dose rate rapidly decreases. However, if the worker is very close to the patient, the dose rate is quite high even after 40 minutes after exposure [37].

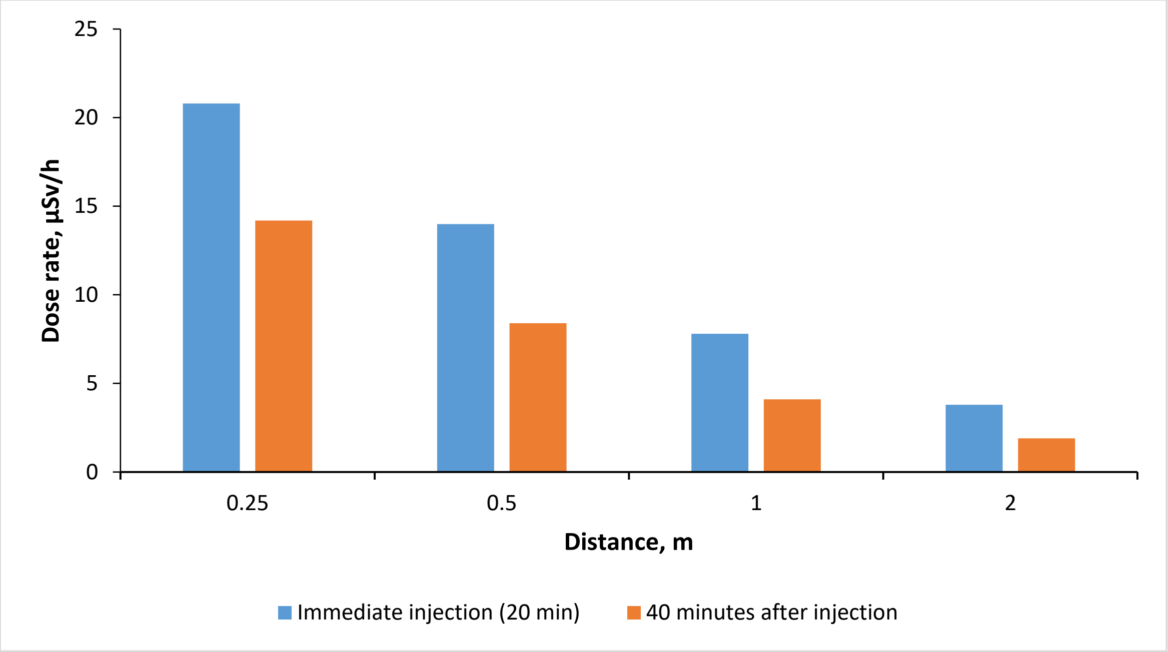


Fig. 6. Dose rate for brain perfusion from 0.25-1 meter distance (average dose 370 MBq of 99mTc-ECD radiopharmaceutical) [37]

Shielding implementation in nuclear medicine had a significant impact on the occupational doses of NM personnel. Shielding should be designed so that the individual external dose would be lower than the dose constraint under normal working conditions [25]. Usually, the shielding material is made from lead. Syringe and vial shields, gowns, shielded screens are mostly used in NM.

Demir et al. [38] investigated whole body and finger doses for 5 nuclear medicine technologists working with ^{18}F-FDG 6 months without and 6 months with added shielding precautions in their practice (lead-equivalent shielding for a sterile syringe which was made from tungsten (thickness – 12.7 mm) and a lead container for the shielded syringe (dimension of 10 × 10 × 20 cm^3, wall thickness – 1.8 cm)). Whole body and finger measurements were performed using TLD-100 dosimeters. The average ^{18}F-FDG activity for one patient was 518 MBq.

It was found that the whole-body annual dose was 1.36 times lower compared with the dose when the shielding was not applied. The Hp(10) dose was 7.82, 5.76 mSv before and after shielding precautions, respectively [38].

Finger doses were also obtained to be lower after implementation of shieldings. The annual finger dose for left and right hand was 0.34, 0.45 µSv/MBq and 0.25, 0.34 µSv/MBq before and after shielding precautions, respectively [38].

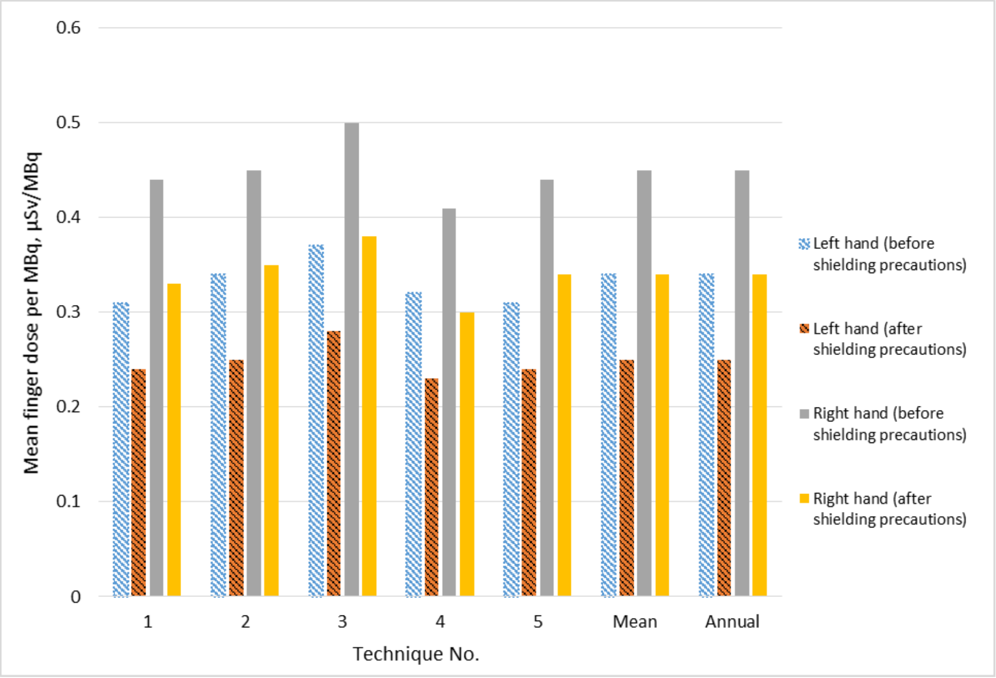


Fig. 7. Demir et al. study results [38]

1.3. Thermoluminescent dosimetry

TLD is one of the most used and accurate dosimetry methods worldwide. TLDs are used for monitoring a wide variety of occupational exposures, ranging from low-risk medical exposures (e.g. radiography) to high-risk exposures (e.g. nuclear medicine) [39].

The advantages of TLD use as the main method for occupational dose assessments are as follows [40]:

- reusability;
- high sensitivity and accuracy (sensitivity to small doses);
- linearity of response to dose;
- ease of processing;
- variability of shapes and sizes (e.g. small sized solid TLDs can be used for extremity dose assessment);
- relative energy independence;
- reasonable resistance to corrosion;
- they are nearly tissue equivalent.

1.3.1. Thermoluminescence process

TL dosimetry is based on emission of light from a semiconductor or an insulator which absorbs energy from ionising radiation and then is heated. Perfect crystal without any lattice defects do not have energy levels between valance (VB) and conduction bands (CB) and cannot produce thermoluminescence, when a crystal has some lattice, it is locally distorted resulting in rise to localised energy levels between the VB and CB. Usually, the crystal is not perfect and has defects. These crystal defect sites can be divided into main two types [41]:

1. Defects inherently present in the material. The example of this type is a negative ion vacancy that traps an electron (F centre).

2. Defects produced by external factors (e.g., adding impurities into the sample (doping)). In this type, a lattice vacancy is created when a higher valence impurity ion is added to the position of a lattice ion (e. g. divalent lattice doped with a trivalent cation impurity).

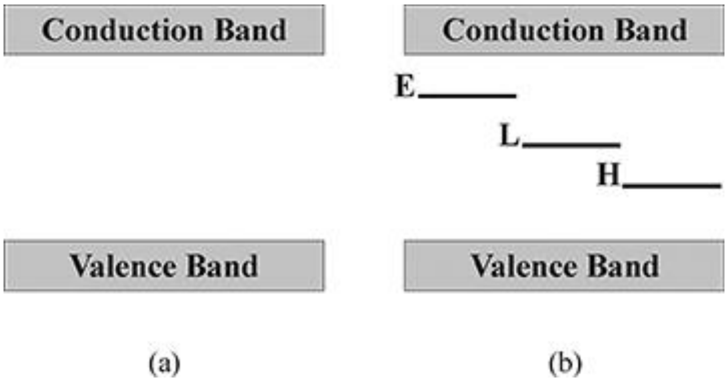


Fig. 8. Ideal crystal (a), imperfect crystal (b) [42]

When a TLD material is irradiated, excited electron moves from VB to CB leaving hole in a VB. A vacancy which was created in VB is called a positive hole. The electron and hole are free to move in their respective bands until they recombine or become trapped. When a crystal is heated, the chance that an electron will break free from the trap rapidly rises and is described by the Arrhenius Equation 3 [41]:

$$p = s \exp\left(-\frac{E}{kT}\right) \qquad (3)$$

where p is the probability per unit time, s – attempt-to-escape factor (in a simple model it is a constant in order of the lattice vibration frequency) and is equal to 10^{12}-10^{14} s^{-1}; E – activation energy required to release and electron from the trap to CB, k – Boltzmann's constant (10^{12}-10^{14} s^{-1}) and T is the absolute temperature.

When these trapped electrons are released, part of them move to lower energy levels and recombine with hole at luminescence centres by emitting a photon of light [43].

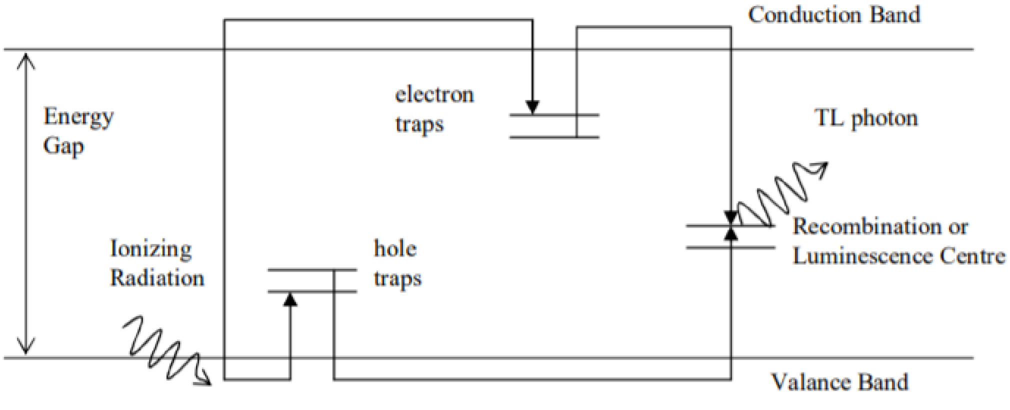


Fig. 9. Principle of thermoluminescence phenomena [43]

The most common way to display TL data is to plot luminescence intensity as a function of temperature, which is referred to as a glow curve and is made up of different peaks that appear at different temperatures. The electron traps in the sample are responsible for these peaks. The number of filled traps, which is proportional to the amount of radiation initially imparted to the TLD, determines the region under each peak [43].

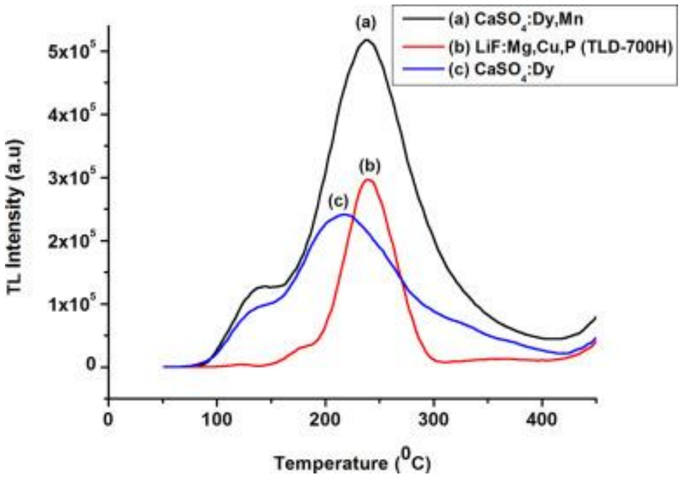


Fig. 10. Example of TL glow curves [44]

1.4. TL materials

Table 2 shows the most common commercially available TL materials and their characteristics. All these dosimeters are used for different purposes. For example, CaF_2:Dy is mainly used for environmental dosimetry while LiF:Mg, Ti is used for research and clinical applications. Lithium fluoride (LiF) and calcium fluoride (CaF_2) with added impurities are the main materials used for TL dosimetry [43].

Table 2. TL materials and their main characteristics [16, 34, 37]

TL material	**Effective atomic number Z_{eff}**	**Main TL peak (°C)**	**Fading**	**Relative sensitivity**	**Dose range**
LiF:Mg, Ti	8.14	200	5% per year	1	10 µGy-1 Gy
LiF:Mg, Cu, P	8.14	210-220	5% per year	40	1 µGy-10 Gy
CaSO4:Dy	15.3	220	8% in six months	30-40	1 µGy-30 Gy
CaF_2:Mn	16.3	260	15% in three months	50	0.1 µGy-100 Gy
CaF_2:Dy	16.3	215	16% in two weeks	30	0.1 µGy-10 Gy
BeO	7.1	190	8% in 2 months	1	0.1 mGy-10 Gy
Mg_2SiO4:Tb	11	200	very slight	40-53	10 µGy-1 Gy
$Li_2B_4O_7$:Mn	7.3	220	4% per month	0.4	10 µGy-10^3 Gy

1.4.1. Lithium fluoride (LiF)

The most widely used radiation dosimeter is lithium fluoride doped with magnesium and titanium (LiF: Mg, Ti), also commercially known as TLD-100 [46]. There are a variety of TLD forms such as extruded rods, powders, chips, pelletized disks, etc. The most popular form for personal dosimetry is chip [40].

Fig. 11. Different forms of TLD's [47]

TLD-100 has an effective atomic number (Z_{eff}) of 8.14 and is nearly tissue equivalent, so its scattering and absorption properties are similar to those of human tissue (Z_{eff} = 7.42) [48]. The TL properties are caused by the presence of impurity concentrations of around 100 and 10 moll ppm for Mg and Ti, respectively. While Ti is involved in the recombination process, Mg is involved in the trapping event [48].

TLD-100 glow curve includes glow peaks that are overlapping. The main peak used for dosimetric applications is No. 5 which appears at 200-210 °C. Peaks 6-13 are received when phosphor is heated up to 450 °C [49] (Fig. 12). Glow peak No. 5 as the dosimetric peak is chosen because it exhibits a half-life of the order of many years and the fading effect is negligible.

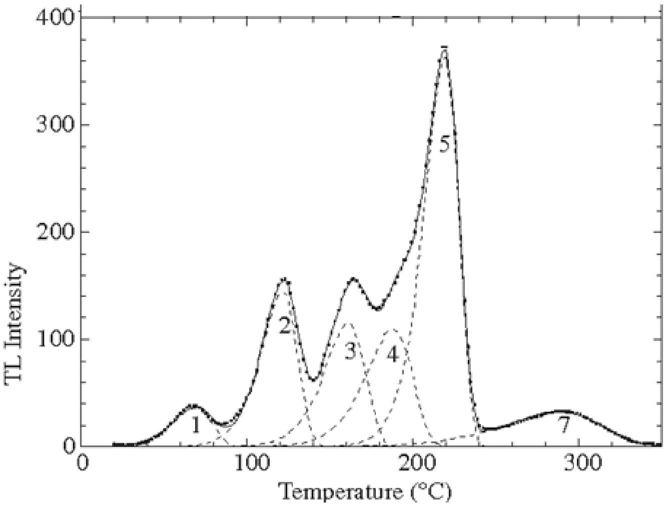


Fig. 12. TLD-100 glow curve [50]

TLD-100 is made up of Li in its normal isotopic concentration, with 7.5 percent ^{6}Li and 92.5 percent ^{7}Li, respectively. The percentage of Li isotopes in the material can change the use field of dosimeter. For example, TLD-600 which is enriched with ^{6}Li (95.6% ^{6}Li and 4.4% ^{7}Li) is commonly used for neutron dosimetry while the TLD-700 enriched with ^{7}Li (99.93% ^{7}Li and 0.07% ^{6}Li) is used for betta and gamma radiation [21].

Another LiF based material is doped with magnesium, copper and phosphorous (LiF:Mg, Cu, P), commercially known as TLD-100H. It has the same Z_{eff} as TLD-100 but it has about 40 times higher sensitivity, is less energy dependent and has wider dose range. The main disadvantage of this type of dosimeter is that annealing at temperatures above 270°C reduces dosimeter sensitivity as the state of Cu impurities changes from Cu^{+} to Cu^{2+} [51]. TLD-100H glow curve is simpler than TLD-100, it has only several overlapping peaks. The main dosimetric peak is No. 4 which appears at approximately 210-220°C [51].

Freire et al. [52] compared TLD-100 and TLD-100H dosimeters for extremity monitoring. Each LiF based dosimeter variety was studied for reproducibility, energy dependence, linearity and residual signal. For the energy dependence and linearity measurements, 5 random detectors of TLD-100 and TLD-100H were used. They were irradiated and read simultaneously with reading cycle parameters that are shown in Table 3. Linearity was tested with 1, 2, 5, 10, 20, 50 and 100 mSv for ^{137}Cs and N120 kVp radiations.

Table 3. Reading cycle parameters of TLD-100 and TLD-100H detectors [52]

	LiF:Mg, Ti (TLD-100)	**LiF:Mg, Cu, P (TLD-100H)**
Pre-heating	10 s at 130 °C	6 s at 140 °C
Heating rate (°C/s)	15	15
Max. temperature reached (°C)	300	250
Reading cycle duration (s)	13.3	1

It was found that the TLD-100 dosimeters show wider energy dependence than TLD-100H. In comparison to LiF:Mg,Ti, LiF:Mg,Cu,P had a higher residual signal [52].

Both TLD-100 and TLD-100H showed linear behaviour. The results when TLDs were irradiated with ^{137}Cs source were better compared with N120 kVp radiations as they are closer to the unity [52].

Both TLDs produced consistent reproducibility results over the course of 10 irradiation cycles. All results, including the error bars, were found to be contained by ±2% guides around unity. In order to prevent underestimations of the measured extremity dose, ^{137}Cs was recommended for dose calibration [52].

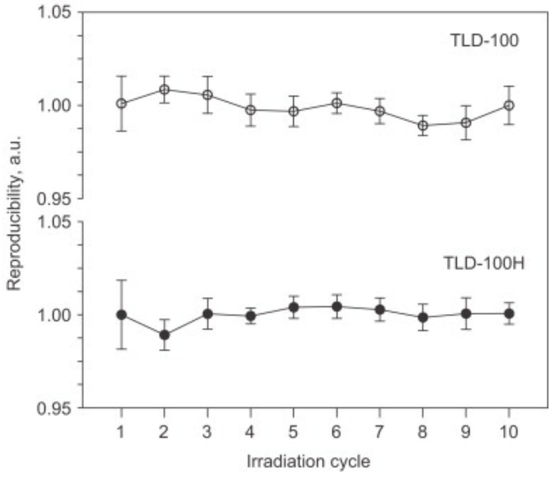


Fig. 13. Reproducibility of TLD-100 and TLD-100H [52]

1.4.2. Calcium fluoride (CaF_2)

Calcium fluoride doped with manganese (CaF_2:Mn), also known as TLD-400 is one of the main CaF_2 based TL material. It is mainly used for environmental and high-dose measurements [48-49]. The effective atomic number Z_{eff} of 16.3 is contrary than LiF-based materials and its properties are not similar to human tissue. CaF_2:Mn material has a very simple glow curve and only a single peak appears at about 260°C [55]. The emission spectrum of TLD-400 has its maximum on 500 nm.

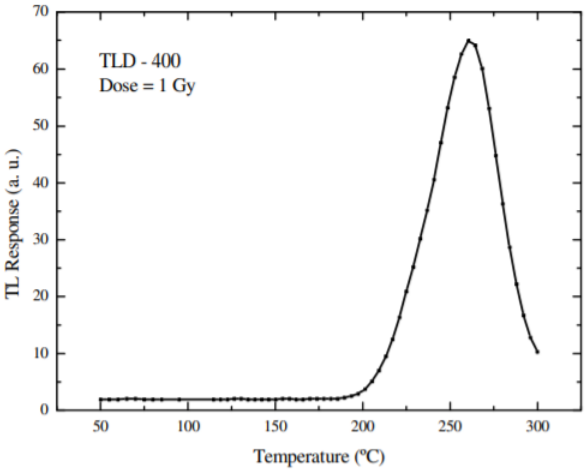


Fig. 14. Glow curve of TLD-400 [55]

It is assumed that the TL curve highly depends on the doping agent Mn^{2+} concentration and distribution. Danilkin et al. [56] found that the TL curve of LiF:Mn demonstrates one high-temperature peak when CaF_2 is doped with higher Mg^{2+} concentrations. The most appropriate concentration of Mg^{2+} was found to be 2.1-2.5% mol as the lower concentrations in TL glow curve show several peaks that are overlapping.

CaF_2 doped with dysprosium (Dy) nanoparticles (CaF_2:Dy), also known as TLD-200 is used for radiation dosimetry. The sensitivity of TLD-200 is about 20-30 times greater compared with TLD-100. Because of its high sensitivity, it has been widely used in environmental and personnel radiation dosimetry, regardless of some issues such as anomalous fading and poor energy response due to its high Z_{eff} (16.3) compared to tissue (7.42). The glow curve of this type of TL dosimeters is more complicated than TLD-400, also it is more sensitive to light [57]. The main dosimetric peak is obtained at about 215-220°C.

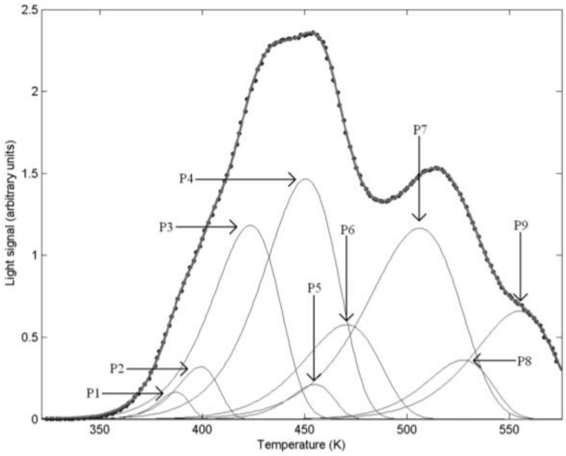


Fig. 15. Glow curve of TLD-200 (9 peaks)

El-Sayed et al. [58] compared sensitivity and dose response to gamma radiation of TLD-100 and TLD-200. The sensitivity was measured by irradiating TL materials with a dose from 5 µGy to $5x10^4$ Gy. The readout procedure was performed 24 hours after irradiation. During this measurement, it was found that the TLD-200 sensitivity is 9-20 greater than TLD-100.

For the dose response experiment, TLDs were irradiated with the same dose range from $5x10^{-6}$ Gy to $5x10^4$ Gy. It was observed that a linear TLD-100 response is from $5x10^{-5}$ Gy to about 5 Gy and above 5 Gy the response is supralinear up to $2x10^3$ Gy while the linear dose response for TLD-200 is from $5x10^{-5}$ Gy up to about 10 Gy (response is supralinear up to $2x10^2$ Gy) [58].

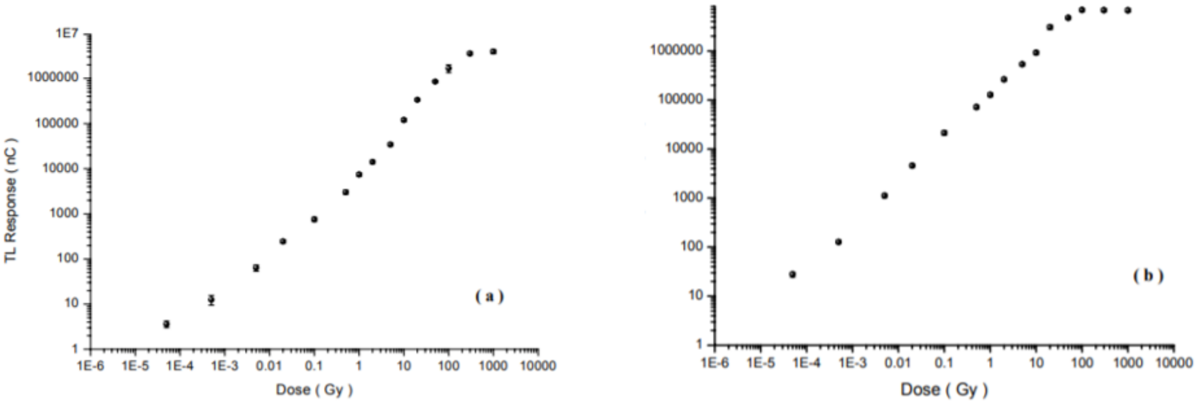


Fig. 16. Dose response of TLD-100 (a) and TLD-200 (b) [58]

1.4.3. Thickness and composition dependence

Moradi et al. [59] evaluated thickness and composition dependence of TLDs relative dose sensitivity using Monte Carlo simulations. For this study, three types of TLD materials made of LiF:Mg,Ti, CaF_2:Mn and SiO_2 with thicknesses of (0.125 – 1) mm were used. The element composition and densities of TLD materials are shown in Table 4.

Table 4. Main characteristics of TLD materials

Material	**Density (g/cm^3)**	Z_{eff}	**Elemental composition, %**
LiF:Mg,Ti	2.64	8.14	Li: 26.72, F: 73.259, Mg: 0.02, Ti: 0.001
CaF_2:Mn	3.18	17.12	Ca: 50.46, F: 47.84, Mn: 1.7
SiO_2	2.15	12.22	Si: 46.67, O: 53.33

It was found that the largest deviations were obtained for 0.125 mm TLDs. The deviation of the f_{rel} from unity at 10 cm depth, when the thickness was 0.125 mm, for lithium fluoride was -1.2% and for calcium fluoride was +2.8% while the values when 1 mm thickness dosimeters were used were +0.4 and -1.5%, respectively. Also, it was concluded that higher density and Z_{eff} dosimeters needed a larger correction and that the density of a dosimeter has a greater impact on the field perturbation than Z_{eff} [59].

1.4.4. Energy dependence

The energy dependence on TL response was evaluated by Maia et al [60]. Different TL dosimeters were evaluated in standard diagnostic X-ray beams (50, 80, 100, 120 and 150 kV were used). As seen from the Fig. 17, TLD-100 has a flat energy dependence compared with other TL materials. The highest relative response was observed for CaSO4:Dy dosimeters and TLD-200.

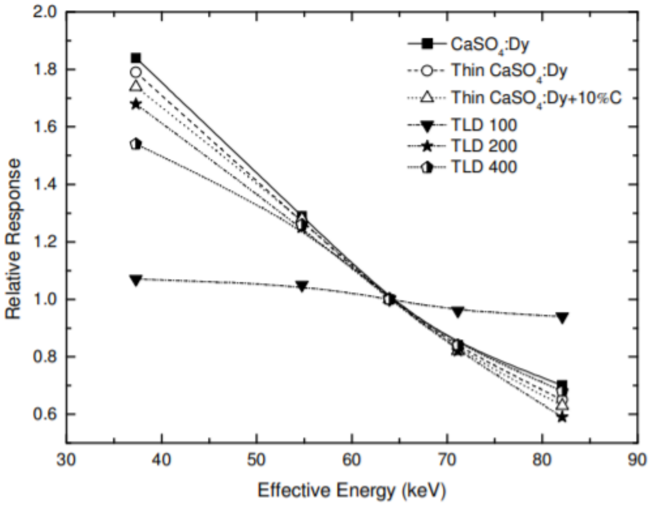


Fig. 17. Energy dependence of the TL response [60]

1.5. Technetium-99m and Fluorine-18 specifications

Diagnostic nuclear medicine uses wide range of radionuclides including ^{123}I, ^{133}Xe, ^{201}Tl, ^{82}Rb, etc. ^{99m}Tc and ^{18}F are the most frequently used radioisotopes in this field. To understand the use of these radionuclides, their specifications, such as half-life, decay, and production must be explained.

1.5.1. Technetium-99m

Technetium-99m (^{99m}Tc) is a gamma emitting radionuclide which plays a major role in NM. It is used in approximately 85% of all diagnostic procedures performed every year around the world [61]. This radioisotope is a great choice for SPECT imaging because of its 140-keV gamma-ray emission and 6.01-hour half-life [62]. Equation 4 shows the decay of Tc-99m.

$$ {}^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma \tag{4} $$

The first ^{99m}Tc generator was developed by Walter Tucker and Margaret Greene in 1950s. Powell Jim Richard taking into account the main properties of this radioisotope encouraged the use of ^{99m}Tc for medical applications in the 1960s. However, a patent of this radioisotope for the use in NM was firstly rejected. After that, another scientist Paul Harper was interested in ^{99m}Tc. He showed that the radionuclide is effective for imaging organs such as brain, liver or thyroid and made a huge impact on ^{99m}Tc use in NM nowadays [63].

Fig. 18. First ^{99}Mo/^{99m}Tc generator [63]

^{99m}Tc is produced from a molybdenum-99 (^{99}Mo). The main advantage of the use of this radioisotope is that 66 hours ^{99}Mo radioactive half-life give sufficient amount of time to bring it to hospitals and to extract chemically ^{99m}Tc [62].

In ^{99}Mo/^{99m}Tc generators, ^{99}Mo in the form of molybdate ion (MoO_4^{2-}) is bonded to aluminium oxide (Al_2O_3) on a column. Decaying molybdenum forms pertechnetate ion (TcO_4^-). This form of technetium is less tightly bound to Al_2O_3 and can be eluted from the column with 0.9% NaCl solution. During this process, the daughter radionuclides are isolated free of contamination from the parent [62].

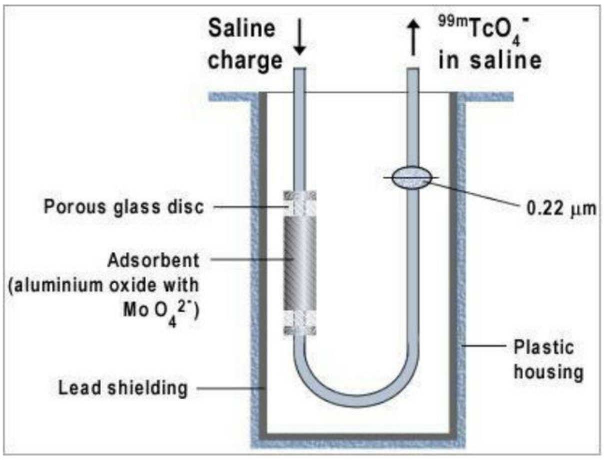


Fig. 19. Components of ^{99}Mo/^{99m}Tc generator [64]

^{99m}Tc- labelled radiopharmaceuticals have wide diagnostic applications in planar scintigraphy and SPECT imaging. They are used to diagnose bone, heart, kidneys, brain, thyroid, liver, and lungs diseases. Table 5 shows the main development of ^{99m}Tc radiopharmaceuticals suitable for various diagnostic NM procedures [65].

Table 5. ^{99m}Tc- labelled radiopharmaceuticals and its use in diagnostic nuclear medicine [65]

Radiopharmaceutical	**Application**
99mTc-Medronate (MDP)	Bone scintigraphy
99mTc-Tetrofosmin	Myocardial perfusion
99mTc-Oxidronate (HDP)	Bone scintigraphy
99mTc-D,L-HMPAO	Brain perfusion
99mTc-DTPA	Renal imaging
99mTc-Pertechnetate	Thyroid imaging, salivary glands
99mTc-MAG$_3$	Renal perfusion
99mTc-colloids	Liver scintigraphy
99mTc-DMSA	Kidney scan
99mTc-albumin macroaggregate	Lung perfusion
99mTc-l,l-ECD	Brain perfusion

1.5.2. Fluorine-18

Fluorine-18 (^{18}F) is a radioisotope most frequently used in PET due to its 109.7 min half-life and a clean beta plus (β^+) decay profile (97% positron emission and 3% electron capture) [66]. Radioisotope decays to stable Oxygen-18 (^{18}O) releasing two particles – a neutrino and a positron. Positron annihilates with an electron and produces two coincident gamma ray photons (γ) of 511 keV 180° apart. PET scanners use detectors that are arranged in a ring around the patient and distinguish the photon pair at the same time in a coincidence event [67] (Fig. 20).

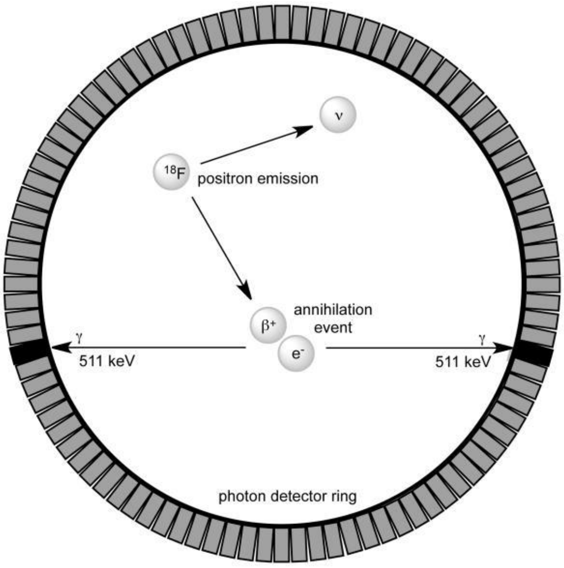


Fig. 20. PET imaging detector and ^{18}F annihilation process [67]

^{18}F is basically produced in a cyclotron. In this case, the target is water enriched with Oxygen-18. Firstly, hydride ions (H^-) which are generated in the ion chamber are accelerated. H^- ions are passed through an electron stripper, which forms protons, just before they are directed onto the target. Interacting protons with a target form ^{18}F (Equation 5) [68].

$$ {}^{18}_{8}O + {}^{1}_{1}p \rightarrow {}^{18}_{9}F + {}^{1}_{0}n + \gamma \qquad (5) $$

^{18}F radioisotope is widely used in oncology, cardiology, and neurology fields. The most common ^{18}F-labelled radiopharmaceutical is 2-[18F]fluoro-2-deoxy-D-glucose (^{18}F-FDG). Wolf et al. performed the first electrophilic fluorination synthesis of this radiopharmaceutical in Brookhaven National Laboratory in 1976 [69]. ^{18}F-FDG helps to show glucose metabolism and to diagnose cancer and cancerous lesions as cancer can be found by increased glucose metabolism in target area [66].

1.6. Literature review summary

NM workers work with open radiation sources – short lived radionuclides such as ^{18}F, ^{99m}Tc and are exposed to ionising radiation internally by inhalation and ingestion of radioactive substances and externally from the patients, vials, and syringes. To evaluate internal doses for NM staff, whole body/organ counting and activity measurements from bioassay samples such as faeces, blood or urine is preferred. Air sampling in the breathing area of the worker or workplace is also used. For the measurements of external doses, workers use active or passive dosimeters. The difference between these types of dosimeters is that active dosimeters show the results immediately, while the readout process for the passive dosimeters must be firstly obtained. Moreover, passive dosimeters accumulate doses during time, and it is the most commonly used type of dosimeters for occupational exposure measurements.

It is assumed that the hand, especially fingertips, of NM personnel is the most exposed part. It was found that fingertips of thumb, index and middle fingers receive the highest doses over the hand and might exceed the recommended 500 mSv annual dose. To evaluate hand occupational doses, TLD method is preferred as these dosimeters are available in different shapes and sizes, also they are accurate and precise. The most commonly used TL dosimeters in dosimetry are LiF and CaF_2 based dosimeters, however LiF:Mg, Ti (TLD-100) and LiF:Mg, Cu, P (TLD-100H) are the most chosen for personal dosimetry because its Z_{eff} 8.14 is similar to those of human tissue ($Z_{eff} = 7.42$).

2. Materials and methods

2.1. TLD-100 chips

For the measurements of hand doses, 90 units of TLD-100 chips were used. The thickness of these dosimeters were 2 mm and the diameter ~4.5 mm. These detectors are a great tool for extremity measurements as they are relatively small and do not cause significant inconvenience for the personnel.

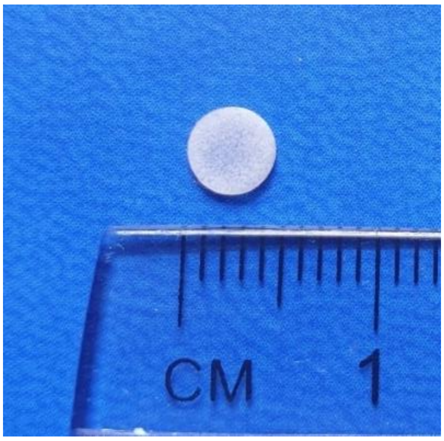


Fig. 21. TLD-100 chip

2.2. Calibration of dosimeters

To produce the measurements on NM workers, dosimeters had to be firstly calibrated with known doses. All the measurements were done at Vilnius University Hospital Santaros Klinikos Nuclear Medicine Department. 50 units of TLD-100 chips were calibrated with ^{99m}Tc source and 40 units were calibrated with ^{18}F source. The doses which were used for calibration with each radioisotope are shown in Table 6. Calibration doses for ^{18}F radionuclide were selected in a lower range compared with ^{99m}Tc because during the same time the total activity with which personnel work is lower. Due to higher ^{99m}Tc activities, more attention was paid to hand doses when working with this radionuclide.

Table 6. Doses used for TLD-100 calibration

Radioisotope	**Dose, mSv**			
99mTc	0.50	1.00	2.00	4.00
18F	0.25	0.50	1.00	2.00

The distance between the source and the chips was 8 cm. The activity of radionuclide was in a range of (900-1100) MBq for ^{99m}Tc and (150-400) MBq for ^{18}F calibration measurements. All the dosimeters were placed in plastic bags and numbered.

Fig. 22. Calibration procedure

2.3. TLD readout procedure

TLD-100 dosimeters were read at Kaunas University of Technology using RIALTO TLD reader. The system consists of a monitor, keyboard, reading unit and a nitrogen gas tank.

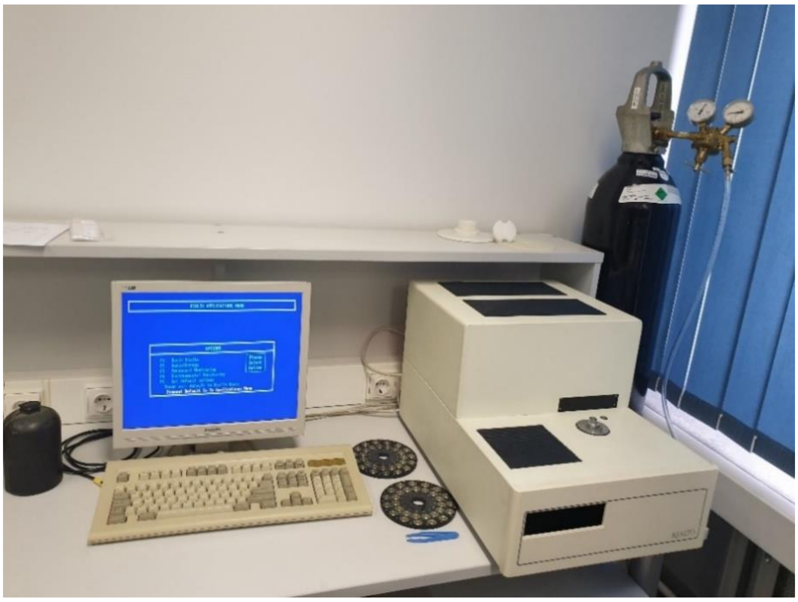


Fig. 23. RIALTO TLD system

For the readout procedure, dosimeters have to be put into a detector carrousel, which has 30 heating trays, using plastic tweezers to ensure that detectors are clean, not scratched and the oil from fingers does not contaminate the TLDs [21].

Fig. 24. Detector carrousel

Two trays with dosimeters are put inside the chamber automatically above the heater element at once as the RIALTO TLD device has two sealed measuring chambers with separate recording and heating system for each chamber allowing to read two dosimeters simultaneously. To ensure the accuracy and repeatability of the measurements, the temperature of the heating elements is maintained at a constant with the accuracy of one-degree. When the dosimeters are heated, they produce light which passes through the infrared filters and enters the photomultiplier. Once in the photomultiplier, the photons of light are converted into an electrical signal and then digitized [70].

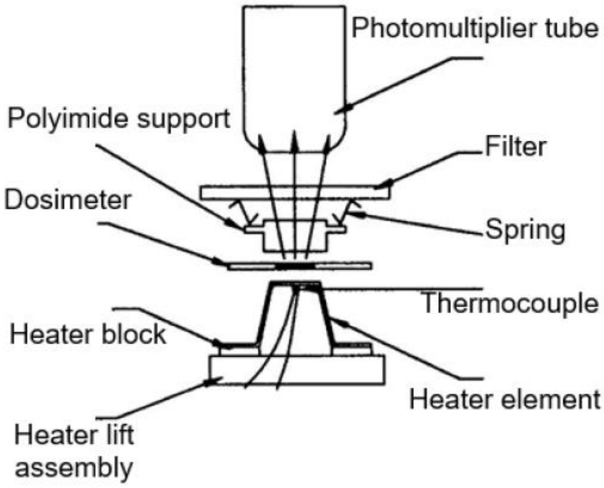
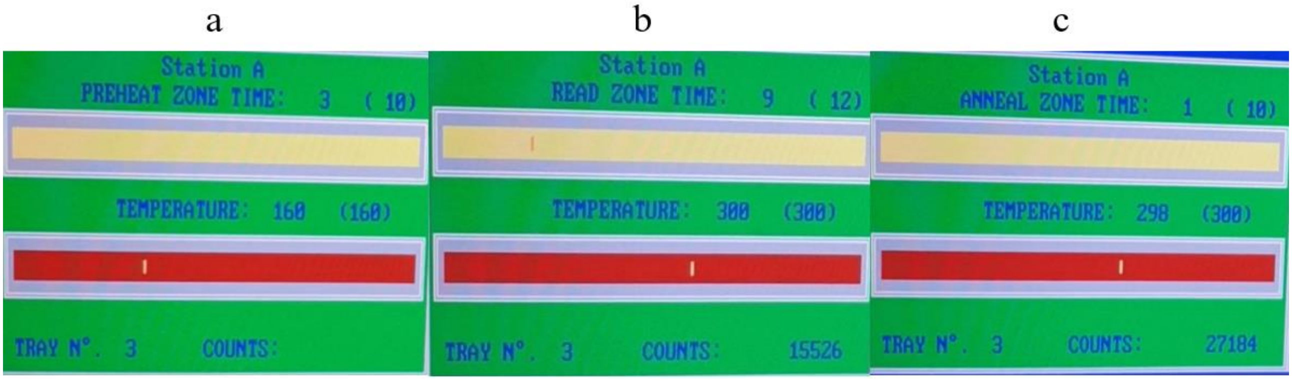


Fig. 25. Structure of RIALTO TLD reader [70]

RIALTO TLD uses multiple stage (step) heating cycle that consists of 3 main zones:

1. Pre-heat zone. Before starting the measurements, the detector is heated up to 160°C to free the unstable low-temperature capture centres. The duration of this step is 10 s.
2. Read-out zone. During this stage, the temperature is raised up to 300°C and the data of the produced light intensity are collected. The duration of this step is 12 s.
3. Annealing zone. During this stage, annealing is performed to remove the residual signal and restore the distribution of the capture centres. The duration of this step is 10 s.

Immediately after annealing, the detector is suddenly cooled with nitrogen. Due to this cooling, the same sensitivity is observed in each measurement. The use of nitrogen also helps to reduce oxidation processes of heating element [70].



Station A
PREHEAT ZONE TIME: 3 (10)
TEMPERATURE: 160 (160)
TRAY N°. 3 COUNTS:

Station A
READ ZONE TIME: 9 (12)
TEMPERATURE: 300 (300)
TRAY N°. 3 COUNTS: 15526

Station A
ANNEAL ZONE TIME: 1 (10)
TEMPERATURE: 298 (300)
TRAY N°. 3 COUNTS: 27184

Fig. 26. RIALTO TLD heating cycle zones: a – preheat zone, b – read-out zone, c – anneal zone

2.4. Selection of dosimeters

Not all dosimeters were selected for hand dose measurements. To choose the most accurate dosimeters, the 2σ rule was applied on TLD reading output, dosimeters which results were above ±2σ (mean + 2x standard deviation; mean – 2x standard deviation) limits were rejected.

After the TLD calibration results were obtained and dosimeters were selected, element correction coefficient (ECC) of each chip was calculated using Equation 6:

$$ECC(i) = \frac{<TLE>}{TLE_i} \tag{6}$$

where ECC(i) is the ECC value of dosimeter i, <TLE> is the mean TL efficiency of all TLDs irradiated with the same dose, TLE_i – TLE of specific TLD [71]. ECC value is multiplied with the reading output to make each dosimeter's response equal to the average response of a certain population.

2.5. Hand dose measurements

Hand dose measurements were performed for radiology technologists of Vilnius University Hospital Santaros Klinikos Nuclear Medicine Department who prepare and administer ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals. Dosimeters were attached to both hands at 14 locations (dosimeters No. 1-14, 7 chips on each hand) under the disposable gloves. As mentioned before, NM workers have to wear ring dosimeter on the base of a finger of the dominant hand, and the results can be 2-6 times lower compared with fingertip doses [2]. For this purpose, additional measurement was performed by adding dosimeter No. 15 to determine the difference in dose distribution between the hand (fingertips, palm, wrist) and a typical ring dosimeter carrying location.

Fig. 27. TLDs positions on both hands

Each technician working with ^{99m}Tc wore dosimeters for 5 days. Due to low radionuclide activities, dosimeters were worn for 7 days to perform measurements while working with ^{18}F. The activity per week working with ^{99m}Tc in a hot lab was in a range of (26.80-38.76) GBq (average 31.99 GBq), for injections – (12.01-19.25) GBq (average 14.54 GBq/week). The activity for ^{18}F measurements was 16.65 GBq. The dominant hand of all workers was the right hand. A total of 7 measurements for personnel working in a hot lab and preparing ^{99m}Tc- labelled radiopharmaceuticals, 3 measurements for injection of ^{99m}Tc- labelled radiopharmaceuticals, and 1 measurement for radiology technologist working with ^{18}F radionuclide were performed. Measured doses were normalized per manipulated activity (mSv/GBq). Additionally, average hand doses for both hands were calculated by taking the average value of fingertip, palm and wrist doses.

3. Results

3.1. Calibration and selection of dosimeters

50 TLD-100 dosimeters were irradiated with ^{99m}Tc source and 40 chips were irradiated with ^{18}F source. Dosimeters were selected using the 2σ rule. The distribution of TLD response is shown in Fig. 28 and Appendices 1 and 2.

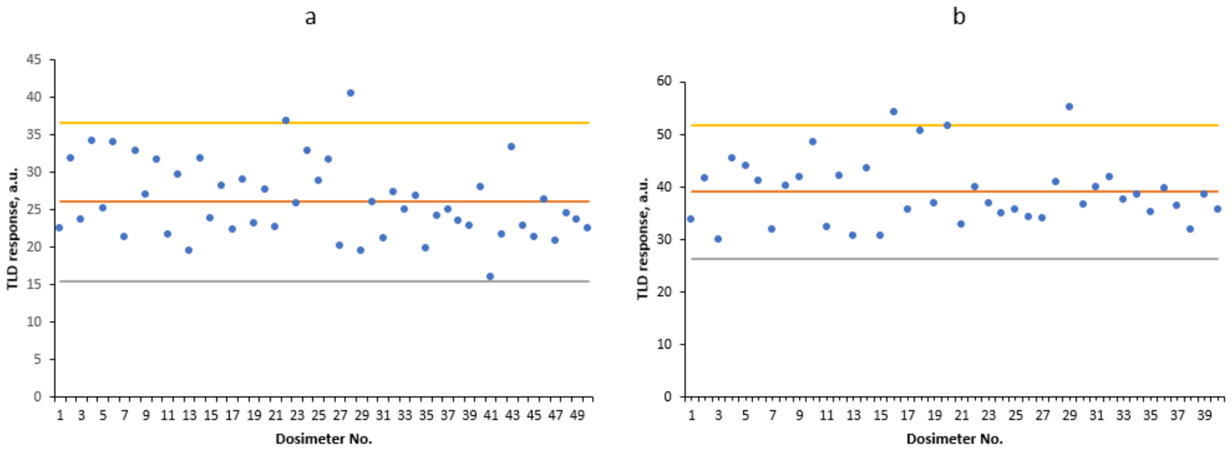


Fig. 28. TLDs response distribution after irradiation with ^{99m}Tc (a) and ^{18}F (b) source (2mSv)

After application of the 2σ rule on dosimeters irradiated with ^{99m}Tc radionuclide, 8 TLDs were rejected. 7 dosimeters were additionally rejected as their dose response was not linear, the dosimeter was dirty or has been broken during the readout procedure. In total, the most accurate 35 dosimeters were selected for measurements with ^{99m}Tc radionuclide. Meanwhile, for ^{18}F irradiated detectors, 5 TLDs were disapproved after the 2σ rule was applied and other 5 detectors were disapproved for the reasons listed above. In total, 30 dosimeters were selected as the most appropriate for hand exposure measurements.

When dosimeters were selected, calibration curves were drawn. As seen in Fig. 29, both calibration curves showed linear dependence. A higher R^2 value was obtained for detectors irradiated with ^{99m}Tc source (0.9982) than irradiated with ^{18}F source (0.9903). However, the difference is relatively small (0.0077) and can be explained by the fact that the dosimeters were irradiated with higher ^{99m}Tc doses.

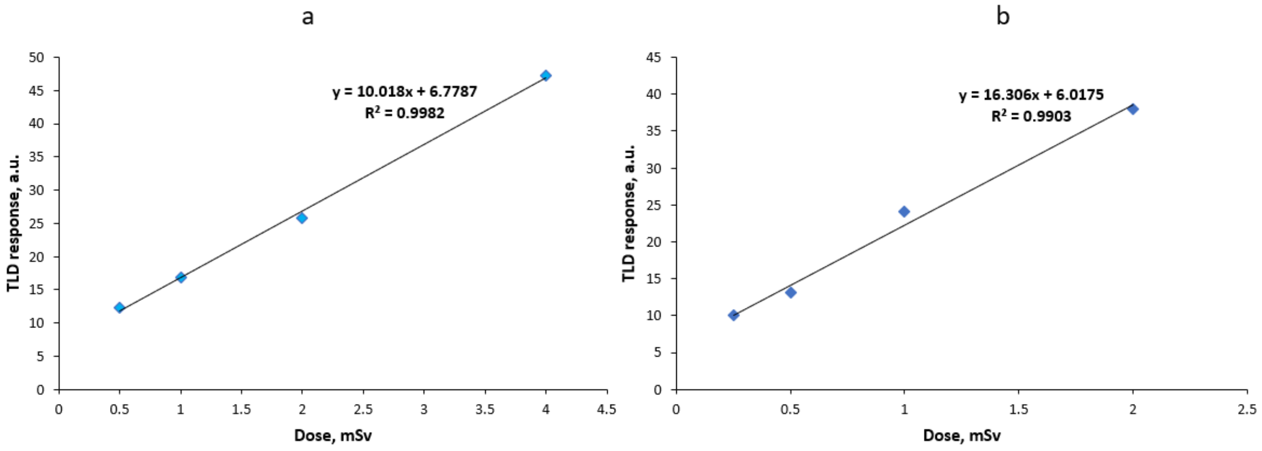


Fig. 29. Calibration curves of ^{99m}Tc and ^{18}F

Element correction coefficient (ECC) which is used to make each dosimeter's response equal to the average response was calculated before and after dosimeter selection. Fig. 30 shows the example of ECC changes when TLDs were irradiated with 2 mSv dose of ^{99m}Tc.

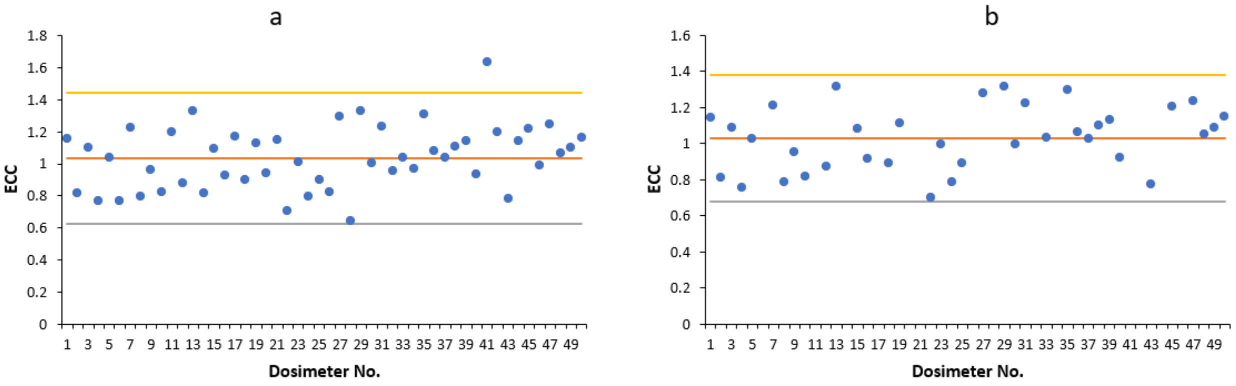


Fig. 30. ECCs distribution before and after dosimeter rejection (2 mSv/ ^{99m}Tc)

As seen in Fig. 30, the outlier was removed, the ECC range reduced from (0.643-1.632) to (0.702-1.320).

3.2. Hand doses

In order to perform hand dose measurements, nuclear medicine workers wore dosimeters on each fingertip, palm and wrist. For additional point (ring dosimeter position), 1 measurement was done for radiology technologist working in a hot lab and 2 measurements for worker injecting ^{99m}Tc- labelled radiopharmaceuticals. Each worker working with ^{99m}Tc wore dosimeters for 5 days (for ^{18}F measurement – 7 days). During the procedures, one dosimeter was lost when changing gloves.

As seen from Table 7 and Table 8, the highest dose obtained while preparing radiopharmaceuticals was by the right thumb tip and resulted in 1.100 mSv/GBq, meanwhile the left hand wrist received the lowest dose and resulted in 0.016 mSv/GBq. Regarding the doses received during the injections, the highest dose was observed in the left index finger tip (0.114 mSv/GBq) and the lowest – in the right hand wrist (0.010 mSv/GBq). Higher left index finger tip doses during injection can be explained by the fact that the worker holds the patient's hand directly at the injection site for greater stability.

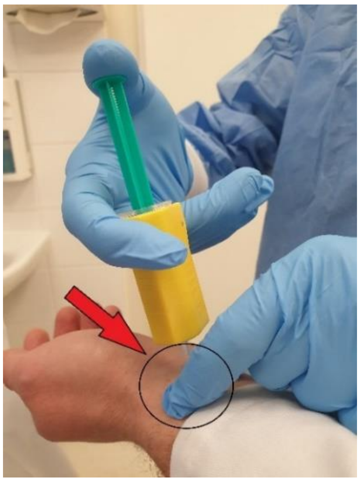


Fig. 31. Example of hand positions during injection

Table 7. Left hand doses of nuclear medicine personnel working with ^{99m}Tc

TLD position	**Dose per unit activity, mSv/GBq**							**Total prepared or injected activity, GBq**	**Worker**
	Thumb tip (1)	Index finger tip (2)	Middle finger tip (3)	Ring finger tip (4)	Pinky tip (5)	Palm (11)	Wrist (13)		
	Dosimeters were worn while preparing radiopharmaceuticals								
	0.135	0.209	0.100	0.068	0.040	0.050	0.016	26.782	A
	0.508	0.543	0.463	0.224	0.243	0.113	0.043	28.195	B
	0.312	0.315	0.195	0.142	0.087	0.097	0.028	34.133	B
	0.271	0.307	0.139	0.100	0.092	0.071	0.029	28.425	C
	0.207	0.332	0.102	0.096	0.063	0.069	0.024	34.453	D
	0.235	0.400	0.286	0.145	0.104	0.064	0.031	33.194	B
	0.249	0.494	0.199	0.110	0.116	0.100	0.043	38.759	D
Average	0.274	0.371	0.212	0.126	0.106	0.081	0.031	31.992	-
Median	0.249	0.332	0.195	0.110	0.092	0.071	0.029	33.194	-
	Dosimeters were worn while injecting radiopharmaceuticals								
	0.053	0.114	0.081	0.052	0.070	0.022	0.029	12.013	B
	0.066	0.081	0.078	0.082	0.081	0.061	0.051	12.349	B
	0.042	0.086	0.052	0.028	0.021	0.053	0.014	19.254	B
Average	0.054	0.094	0.070	0.054	0.057	0.045	0.031	14.539	-
Median	0.053	0.086	0.078	0.052	0.070	0.053	0.029	12.349	-

Table 8. Right hand doses of nuclear medicine personnel working with ^{99m}Tc

TLD position	**Dose per unit activity, mSv/GBq**								**Total prepared or injected activity, GBq**	**Worker**
	Thumb tip (6)	Index finger tip (7)	Middle finger tip (8)	Ring finger tip (9)	Pinky tip (10)	Palm (12)	Wrist (14)	Ring dosimeter position (15)		
	Dosimeters were worn while preparing radiopharmaceuticals									
	0.369	0.227	0.366	0.242	0.120	0.082	0.068	-	26.782	A
	1.100	0.801	0.960	0.628	0.292	0.162	0.075	-	28.195	B
	0.771	0.665	0.596	0.311	0.145	0.135	0.054	-	34.133	B
	-*	0.402	0.439	0.356	0.164	0.093	0.035	-	28.425	C
	0.669	0.440	0.582	0.566	0.153	0.079	0.036	-	34.453	D
	0.914	0.757	0.839	0.259	0.189	0.134	0.068	-	33.194	B
	0.544	0.344	0.537	0.372	0.242	0.100	0.085	0.225	38.759	D
Average	0.728	0.519	0.617	0.391	0.186	0.112	0.060	0.225	31.992	-
Median	0.720	0.440	0.582	0.356	0.164	0.100	0.068	0.225	33.194	-
	Dosimeters were worn while injecting radiopharmaceuticals									
	0.104	0.056	0.114	0.045	0.044	0.088	0.010	-	12.013	B
	0.095	0.077	0.053	0.043	0.049	0.028	0.017	0.046	12.349	B
	0.065	0.055	0.078	0.029	0.024	0.024	0.021	0.042	19.254	B
Average	0.088	0.063	0.082	0.039	0.039	0.047	0.016	0.044	14.539	-
Median	0.095	0.056	0.078	0.043	0.044	0.028	0.017	0.044	12.349	-

* - lost dosimeter.

Fig. 32 shows average doses per GBq of different points of hands for personnel working with ^{99m}Tc in a hot lab. As seen in the figure, the average dominant (right) hand dose was 2.17 times higher compared with the non-dominant (left) hand and resulted in 0.373 and 0.172 mSv/GBq, respectively. Thumb, index finger and middle finger tips were most irradiated for both left and right hands resulting in 0.728, 0.519, 0.617 for the right hand and 0.274, 0.371, 0.212 mSv/GBq for the left hand. The distribution over both hands is also different – for the dominant hand the highest dose was observed in the right hand thumb, meanwhile for the left hand the index finger tip was irradiated the most.

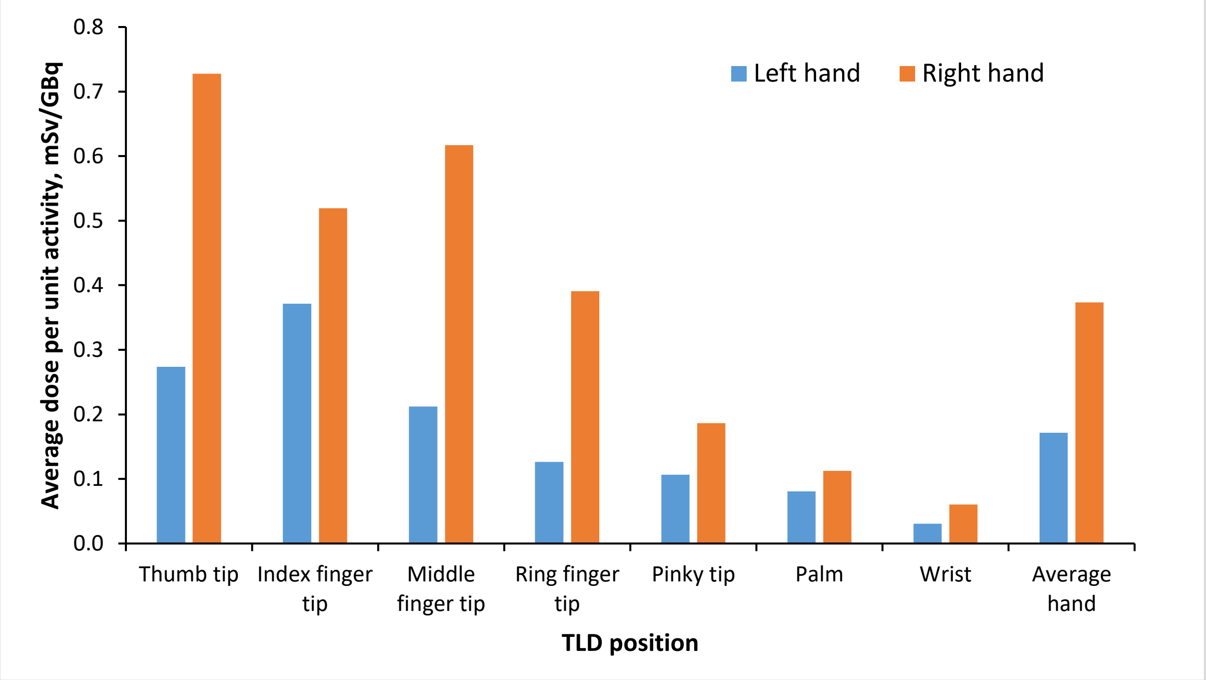


Fig. 32. Hand dose distribution of different points received during preparation of ^{99m}Tc- labelled radiopharmaceuticals

During radiopharmaceutical preparation, one measurement was performed with additional dosimeter placed on the usual monitoring position. As seen from Table 9, the right hand thumb tip dose was 2.42 times higher compared with ring dosimeter position dose. For the left hand wrist, which received the lowest dose, the ratio was only 0.14.

Table 9. The ratio of different hand point dose and ring dosimeter position dose received while working in a hot lab

	Left hand	**Right hand**
TLD position (i)	$H_p(0.07)_i/H_p(0.07)_{\text{ring dosimeter position}}$, a.u.	
Thumb tip	1.22	2.42
Index finger tip	1.65	1.53
Middle finger tip	0.94	2.39
Ring finger tip	0.56	1.65
Pinky tip	0.47	1.08
Palm	0.36	0.45
Wrist	0.14	0.38

In terms of the doses received during administration of ^{99m}Tc- labelled radiopharmaceuticals, the left hand (the average dose 57.943 µSv/GBq) received 1.09 times higher dose than the right hand (the average dose 53.329 µSv/GBq). In this case, the highest average doses were obtained by index finger tip of the left hand, thumb tip and middle finger tip of the right hand and resulted in 93.755, 88.249 and 81.674 µSv/GBq, respectively.

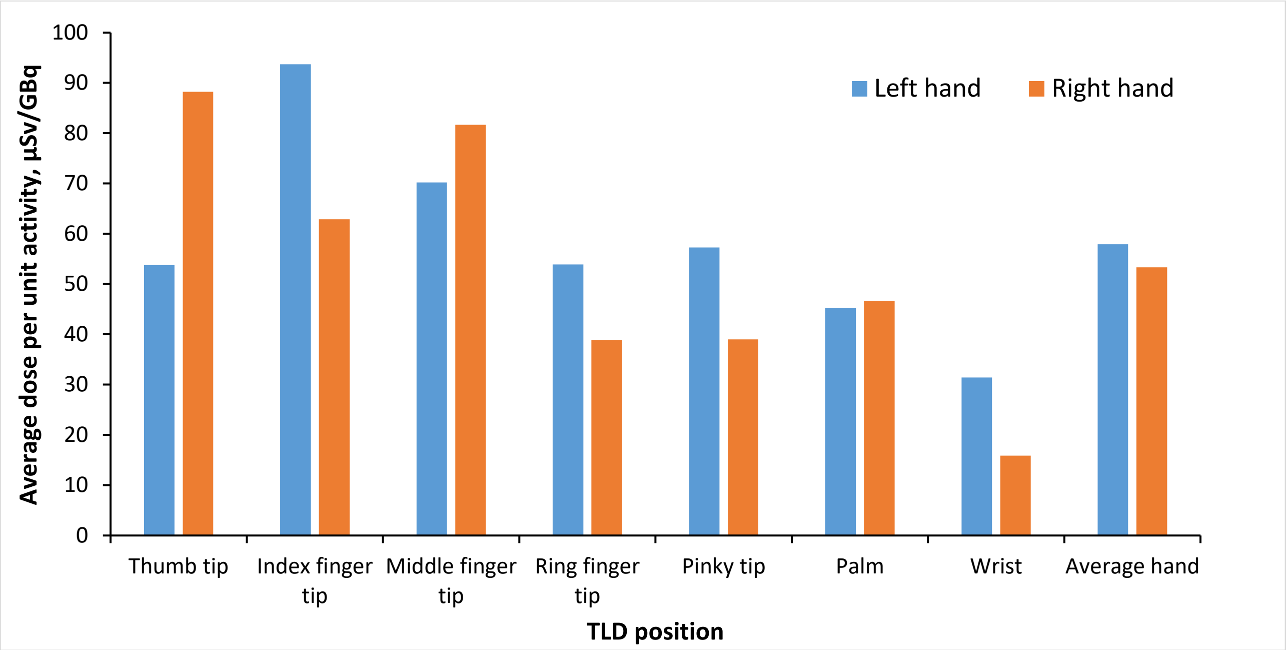


Fig. 33. Hand dose distribution of different points received during injection of ^{99m}Tc- labelled radiopharmaceuticals

During two out of three measurements for NM worker injecting radiopharmaceuticals, TLD chip was additionally attached on ring dosimeter position. During one measurement, the highest dose was obtained by the right hand thumb tip, meanwhile, during the other measurement, the highest dose was received by the left hand index tip. However, both times the highest dose was 2.05 times higher compared with the dose from the ring dosimeter position.

Table 10. The ratio of different hand point dose and ring dosimeter position dose received while injecting radiopharmaceuticals

	Left hand	**Right hand**	**Left hand**	**Right hand**
TLD position (i)	$H_p(0.07)_i/H_p(0.07)_{\text{ring dosimeter position}}$, a.u.		$H_p(0.07)_i/H_p(0.07)_{\text{ring dosimeter position}}$, a.u.	
Thumb tip	1.43	2.05	0.99	1.56
Index finger tip	1.75	1.66	2.05	1.32
Middle finger tip	1.67	1.13	1.24	1.87
Ring finger tip	1.76	0.93	0.67	0.69
Pinky tip	1.74	1.06	0.51	0.57
Palm	1.31	0.61	1.25	0.56
Wrist	1.09	0.37	0.34	0.50

Comparing the doses while preparing and injecting ^{99m}Tc- labelled radiopharmaceuticals, the average hand dose while working in a hot lab was 2.97 and 7.04 times higher than injecting radiopharmaceuticals for the left and right hand, respectively. Lower doses for the administration can be explained by the fact that the syringe is shielded with 2 mm tungsten and that the contact time with the radioactive source is relatively low (only a few seconds).

Table 11. The ratio of average hand dose while preparing and injecting ^{99m}Tc- labelled radiopharmaceuticals

Hand	**Average hand dose while preparing radiopharmaceuticals, mSv/GBq**	**Average hand dose while injecting radiopharmaceuticals, mSv/GBq**	**Ratio, a.u.**
Left	0.172	0.058	2.97
Right	0.373	0.053	7.04

Table 12 summarizes hand dose results of different studies received while preparing and injecting ^{99m}Tc- labelled radiopharmaceuticals. In most cases, the right hand thumb received the highest doses, only Wrzesień et al. [72] found the thumb of the left hand as the most exposed part. The minimum dose of fingertips varies between 0.01-0.09 mSv/GBq for preparing and injecting radiopharmaceuticals.

Table 12. Summary of extremity doses of nuclear medicine personnel working with ^{99m}Tc

Reference	**Method***	**N workers**	**Measurements per worker**	**Number of measured locations**	**Maximum dose of fingertips, mSv/GBq**	**Minimum dose of fingertips, mSv/GBq**	**Average dose from ring dosimeter, mSv/GBq**
This work	P	4	1-3	15	1.1 (right hand thumb)	0.04 (left hand pinky tip)	0.025
Wrzesień et al., 2008 [72]	P	13	3-4	38	2 (left hand thumb)	0.02 (right middle finger)	0.05
Carnicer et al., 2011 [73]	P	36	4-5	22	2.06	0.03	-
Leide-Svegborn, 2011 [74]	P	3	-	11	0.00012 (right hand thumb)	-	-
Adlienė et al., 2020 [2]	P+I	2	Total 120 measurements of 20 locations	20	1.93 (right hand thumb)	0.09 (left hand pinky finger)	-
This work	I	1	3	15	0.114	0.01 (right hand pinky tip)	0.04
Carnicer et al., 2011 [73]	I	32	4-5	22	0.95	0.01	-
Covens et al., 2007 [75]	I	5	-	36	0.06	0.02	-

*P – preparation, I – injection

1 measurement was performed for evaluation of hand doses of NM personnel working with ^{18}F radionuclide. Due to certain situations (equipment malfunction, worker illness), it was not possible to perform more measurements. As seen in Fig. 34, dose distribution over the hand ranged between (9.75-20.87) µSv/GBq for the right and (12.35-17.19) µSv/GBq for the left hand. The dominant hand dose was 1.15 times higher compared with the non-dominant hand. The most exposed parts were index finger tip of the right hand and thumb tip of the right hand (doses 20.87, 20.45 µSv/GBq), the lowest dose was received by the right hand wrist (dose 9.75 µSv/GBq).

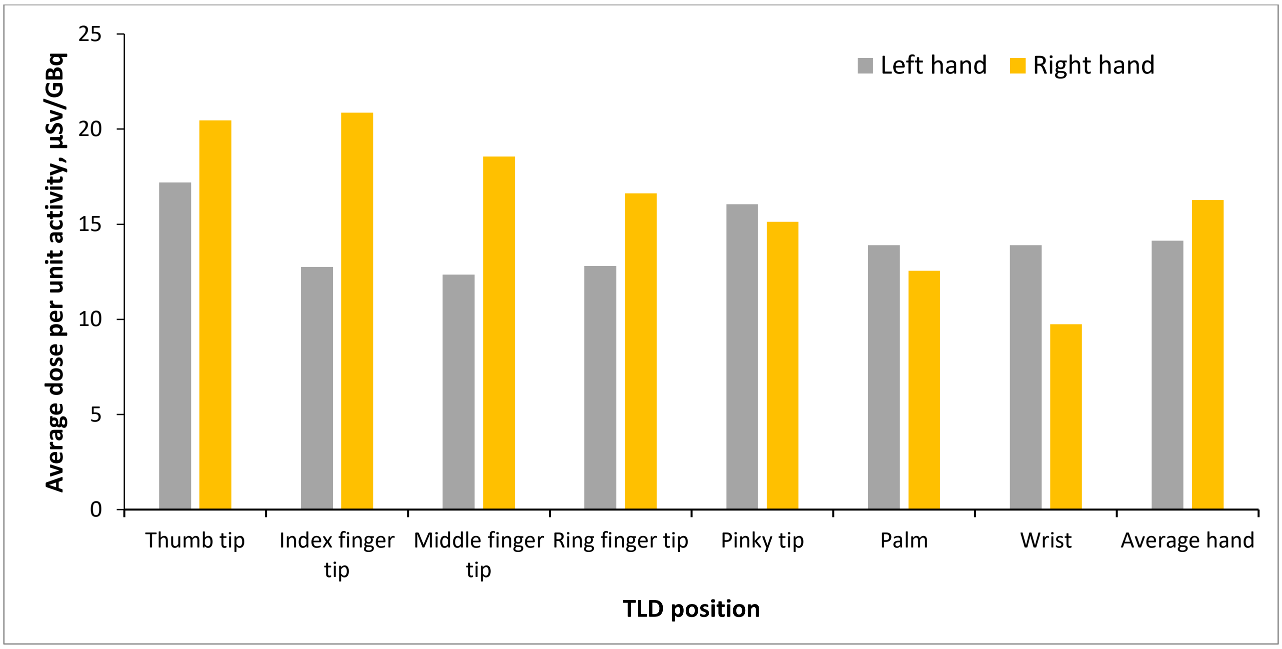


Fig. 34. Hand dose distribution of different points received during preparation of ^{18}F- labelled radiopharmaceuticals

Comparing the average doses received by NM personnel while preparing ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals, the difference is significantly different – doses for the left and right hand are 12.29 and 23.31 times higher when working with ^{99m}Tc. This difference can be explained by the fact that IRIDE dispenser-autoinjector and ALTHEA automatic fractionator are used for the work with ^{18}F radionuclide making the direct contact time with radionuclide much lower [76].

Table 13. The ratio of average hand dose while preparing ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals

Hand	**Average hand dose while preparing ^{99m}Tc- labelled radiopharmaceuticals, mSv/GBq**	**Average hand dose while preparing ^{18}F- labelled radiopharmaceuticals, mSv/GBq**	**Ratio, a.u.**
Left	0.172	0.014	12.29
Right	0.373	0.016	23.31

As seen from Table 14, which summarizes extremity doses of NM personnel working with ^{18}F based on different studies, most of the received maximum doses were lower than 0.1 mSv/GBq and can be explained by the fact that the measurements were obtained by the workers who used automated dispensing and injection systems. Higher doses were observed in Carnicer et al. [72] study, there was no information that during these measurements automated dispensing systems were used.

Table 14. Summary of extremity doses of nuclear medicine personnel working with ^{18}F

Reference	**N workers**	**Measurements per worker**	**Number of measured locations**	**Maximum dose of fingertips, mSv/GBq**	**Minimum dose of fingertips, mSv/GBq**
This work	1	1	14	0.021	0.010
Covens et al., 2010 [77]	2	-	36	~0.018	~0.004
Carnicer et al., 2011 [73]	30	4-5	22	4.43	0.10
Wrzesień, 2018 [78]	3	-	12	0.004	-

Conclusions

1. Measurement results of hand doses of nuclear medicine personnel showed that during preparation of ^{99m}Tc- and ^{18}F- labelled radiopharmaceuticals the right (dominant) hand received 2.17 and 1.15 times higher doses than the left (non-dominant) hand. The most exposed part working in a hot lab with ^{99m}Tc was the tip of the right thumb, and working with ^{18}F, the highest dose was obtained by the right hand index finger tip and resulted in average doses of 0.728 and 0.021 mSv/GBq, respectively. During the radiopharmaceutical injection (^{99m}Tc), the highest average dose was observed in the left hand index finger tip (0.094 mSv/GBq) leading to 1.09 times higher average left hand dose compared with the right hand. During the measurements, the least exposed parts were the palm and the wrist.
2. It was found that the highest doses were obtained while working in a hot lab with ^{99m}Tc. The average doses while preparing ^{99m}Tc- labelled radiopharmaceuticals for the left hand and the right hand were 2.97 and 7.04 times higher compared with administration of ^{99m}Tc- labelled radiopharmaceuticals and 12.29 and 23.31 times higher while preparing of ^{18}F- labelled radiopharmaceuticals. However, in order to accurately compare doses received by personnel working with ^{99m}Tc and ^{18}F, more measurements of ^{18}F should be performed.
3. It was determined that the maximum fingertip dose was 2.1 times higher while injecting and 2.4 times higher while preparing ^{99m}Tc- labelled radiopharmaceuticals compared with the results from usual monitoring position.
4. Based on the results that the highest doses were observed while working in a hot lab with ^{99m}Tc, it could be recommended for the nuclear medicine workers to wear a ring dosimeter on the base of the thumb of the dominant hand.

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List of references

1. LEE W. J., CHOI Y., KO, S., CHA, E. S., KIM, J., KIM, Y. M., HA, Y. W. *Projected lifetime cancer risks from occupational radiation exposure among diagnostic medical radiation workers in South Korea*. BMC cancer, 18(1), 2018, p. 1-10.
2. ADLIENĖ, D., GRICIENĖ, B., SKOVORODKO, K., LAURIKAITIENĖ, J., PUIŠO, J. *Occupational radiation exposure of health professionals and cancer risk assessment for Lithuanian nuclear medicine workers*. Environmental research, 2020.
3. ZOCCARATO, O., MATHEOUD, R., ZANNI, D., VIGNA, L., CAMPINI, R., DE CRESCENZO, S., BRAMBILLA, M. *Extremity doses assessment of nuclear medicine staff involved in 99mTc-radiopharmaceuticals preparation: A multicentre study*. Physica Medica, 32, 2016, p. 230.
4. SANS MERCE, M., RUIZ, N., BARTH, I., CARNICER, A., DONADILLE, L., FERRARI, P., BAECHLER, S. *Extremity exposure in nuclear medicine: preliminary results of a European study.* Radiation protection dosimetry, 144(1-4), 2011, p. 515-520.
5. WRZESIEŃ, M., ALBINIAK, Ł. *Hand exposure of workers in 18F-FDG production centre*. Journal of Radiological Protection, 36(4), N67, 2016.
6. GUILABERT, N., RICARD, M., CHAMOULAUD, K., MAZELIER, C., SCHLUMBERGER. M. *Potential radiation hazard in nuclear medicine*. La Revue du praticien, 65(1), 2015, p. 83-84.
7. H. A. ZIESSMAN AND J. P. O’MALLEY. *Nuclear Medicine: The Requisites E-Book*. Elsevier Health Sciences, 2013, p.1.
8. BRANT, W. E., HELMS, C. A. *Fundamentals of Diagnostic Radiology*. Lippincott Williams & Wilkins, 2012, p. 1228.
9. S. R. CHERRY, J. A. SORENSON, AND M. E. PHELPS. *Physics in Nuclear Medicine E-Book*. Elsevier Health Sciences, 2012, p. 1-5 .
10. S. YANDRAPALLI, Y. PUCKETT. *SPECT Imaging*. StatPearls, Treasure Island (FL): StatPearls Publishing, 2021.
11. ALKHORAYEF, M., MAYHOUB, F. H., SALAH, H., SULIEMAN, A., AL-MOHAMMED, H. I., ALMUWANNIS, M., BRADLEY, D. A. *Assessment of occupational exposure and radiation risks in nuclear medicine departments.* Radiation Physics and Chemistry, p. 170, 2020.
12. R. ASTUDILLO, A. HERMOSILLA, G. DÍAZ-LONDOÑO, M. GARCÍA. *Assessing the need for a routine monitoring program in three Nuclear Medicine centers in Chile*. Radioprotection, vol. 50, no. 2, 2015, p. 141–144.
13. INTERNATIONAL LABOUR ORGANIZATION. *Convention C115 - Radiation Protection Convention, 1960 (No. 115)* [online]. ILO, 1960 [viewed 13 March, 2021]. Available from: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100_INSTRUMENT_ID:312260:NO
14. BEVELACQUA, J. JA. *Practical and effective ALARA*. Health physics, 98(2), 2010, p. 39-47.
15. RADIATION PROTECTION CENTRE. *Annual Report of 2019* [online]. RSC, 2020 [viewed 15 March 2021]. ISSN 2351-5953. Available from: https://www.rsc.lt/index.php/pageid/331
16. INTERNATIONAL ATOMIC ENERGY AGENCY. *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*. Vienna, 2014, p. 132-133.
17. INTERNATIONAL ATOMIC ENERGY AGENCY. *Assessment of Occupational Exposure Due to External Sources of Radiation*. Vienna, 1999, p. 8.
18. INTERNATIONAL ATOMIC ENERGY AGENCY. *Applying Radiation Safety Standards in Nuclear Medicine*. Vienna, 2005, p. 38.
19. FERNANDEZ, J. C., AMPARADO, J. R., ROMALLOSA, K. M. *Dependence of Response of Active Personal Dosimeters on Different Calibration Methods.* Philippine Journal of Science, 148(4), 2019.

20. RISTIC, G. S. *Radiation dosimeters for medical use*. In Conference on Medical Physics and Biomedical Engineering, 2013, p. 59-64.
21. KRY, S. F., ALVAREZ, P., CYGLER, J. E., DEWERD, L. A., HOWELL, R. M., MEEKS, S., MIHAILIDIS, D. *AAPM TG 191: Clinical use of luminescent dosimeters: TLDs and OSLDs*. Medical physics, 47(2), 2020, p.21 .
22. SATO, F., ZUSHI, N., NAGAI, T., TANAKA, T., KATO, Y., YAMAMOTO, T., IIDA, T. *Development of radiophotoluminescence glass dosimeter usable in high temperature environment*. Radiation measurements, 53, 2013, p. 8-11.
23. BENALI, A. H., ISHAK-BOUSHAKI, G. M., NOURREDDINE, A. M., ALLAB, M., PAPADIMITROULAS, P. *A comparative evaluation of luminescence detectors: RPL-GD-301, TLD-100 and OSL-AL2O3: C, using Monte Carlo simulations*. Journal of instrumentation, 12(07), 2017.
24. OLKO, P. *Advantages and disadvantages of luminescence dosimetry*. Radiation Measurements, 45(3-6), 2010, p. 506-511.
25. INTERNATIONAL ATOMIC ENERGY AGENCY. Occupational Radiation Protection, IAEA Safety Standards Series No. GSG-7. IAEA, Vienna, 2018, p. 139-259.
26. PODGORSAK, E. B. *Review of radiation oncology physics: a handbook for teachers and students*. Vienna, Austria: IAEA, 2013, p. 114.
27. INTERNATIONAL ATOMIC ENERGY AGENCY. *Practical Radiation Technical Manual*. Vienna, 2004, p. 34.
28. CIRAJ-BJELAC, O., CARINOU, E., VANHAVERE, F. *Use of active personal dosimeters in hospitals: EURADOS survey*. Journal of Radiological Protection, 38(2), 2018, p. 702.
29. ICRP. *Radiation Dose to Patients from Radiopharmaceuticals - Addendum 3 to ICRP Publication 53*. ICRP Publication 106. Elsevier, 2008, p.180.
30. RADIACINĖS SAUGOS CENTRO DIREKTORIUS. *V-91 Dėl Radiacinės saugos centro direktoriaus 2007 m. lapkričio 16 d. įsakymo Nr. 63 "Dėl Darbuotojų apšvitos ir darbo vietų stebėsenų atlikomo taisyklių patvirtinomo" pateikimo* [online]. Vilnius, 2020 [viewed 13 May, 2021]. Available from: https://www.e-tar.lt/portal/lt/legalAct/9f6c3bd049de11eb8d9fe110e148c770
31. RADIACINĖS SAUGOS CENTRAS. 2*017–2023 metų gyventojų ir darbuotojų, dirbančių su jonizuojančiosios spinduliuotės šaltiniais, apšvitos stebėsenos programos 2019 metų ataskaita* [online]. RSC, 2020 [viewed 15 March 2021]. Available from: https://www.rsc.lt/index.php/pageid/331
32. MARTIN, C. J. *Strategies for assessment of doses to the tips of the fingers in nuclear medicine*. Journal of Radiological Protection, 36(3), 2016, p. 405.
33. PAQUET, F., ETHERINGTON, G., BAILEY, M. R., LEGGETT, R. W., LIPSZTEIN, J., BOLCH, W., HARRISON, J. D. *ICRP Publication 130: Occupational intakes of radionuclides: Part 1*. Annals of the ICRP, 44(2), 2016, p. 51-53.
34. PAQUET, F., BAILEY, M. R., LEGGETT, R. W., HARRISON, J. D. *Assessment and interpretation of internal doses: uncertainty and variability*. Annals of the ICRP, 2016, p. 202-214.
35. ICRP. *Compendium of Dose Coefficients based on ICRP Publication 6*0. ICRP Publication 119. Ann. ICRP 41(Suppl.), 2012, p. 9.
36. DE MASSIMI, B., BIANCHINI, D., SARNELLI, A., D'ERRICO, V., MARCOCCI, F., MEZZENGA, E., MOSTACCI, D. *Air contamination measurements for the evaluation of internal dose to workers in nuclear medicine departments*. Radiation Physics and Chemistry, 140, 2017, p. 198-201.
37. OHIDUZZAMAN, M., KHATUN, R., REZA, S., KHAN, K. A., AKTER, S., UDDIN, M. F., AHASAN, M. M. *Study of exposure rates from various nuclear medicine scan at INMAS, Dhaka*. IJARIIE, 5(3), 2019, p. 208-218.

38. DEMIR, M., DEMIR, B., YAŞAR, D., SAYMAN, H. B., HALAC, M., AHMED, A. S., USLU, I. *Radiation doses to technologists working with 18F-FDG in a PET center with high patient capacity.* Nukleonika, 55, 2010, p. 107-112.
39. POOYA, S. H., OROUJI, T. *Evaluation of effective sources in uncertainty measurements of personal dosimetry by a Harshaw TLD system*. Journal of biomedical physics & engineering, 4(2), 2014, p. 43.
40. BHATT, B. C., KULKARNI, M. S. *Thermoluminescent phosphors for radiation dosimetry. In Defect and Diffusion Forum*. Trans Tech Publications Ltd, 2014, p. 179-227.
41. BOS, A. J. *Thermoluminescence as a research tool to investigate luminescence mechanisms*. Materials, 10(12), 2017, p. 1357.
42. STRATAKIS, J., PAPADAKIS, A. *Radiation Dose Management of Pregnant Patients, Pregnant Staff and Paediatric Patients*. IOP, 2019, p. 12 .
43. PAU, K. S. *Thermoluminescence studies of naturally ocurring salts relevant to dosimetry obtained from Mizoram*. Doctoral dissertation, Mizoram University, 2013.
44. BAHL, S., LOCHAB, S. P., KUMAR, P. *CaSO4: Dy, Mn: A new and highly sensitive thermoluminescence phosphor for versatile dosimetry*. Radiation Physics and Chemistry, 119, 2016, p. 136-141.
45. KONNAI, A., NARIYAMA, N., OHNISHI, S., ODANO, N. *Energy response of LiF and Mg2SiO4 TLDs to 10–150 keV monoenergetic photons*. Radiation protection dosimetry, 115(1-4), 2005, p. 334-336.
46. FERNÁNDEZ, S. D. S., GARCIA-SALCEDO, R., SANCHEZ-GUZMAN, D., RAMÍREZ-RODRÍGUEZ, G., GAONA, E., DE LEÓN-ALFARO, M. A., RIVERA-MONTALVO, T. *Thermoluminescent dosimeters for low dose X-ray measurements*. Applied Radiation and Isotopes, 107, 20163, p. 340-345.
47. RADPRO: *TLD-Material* [online]. 2021 [viewed 25 March 2021]. Available from: http://www.radpro-int.com/tld-1/tld-material/
48. SINGH, R., KAINTH, H. S. *Effect of heating rate on thermoluminescence output of LiF: Mg, Ti (TLD-100) in dosimetric applications*. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 426, 2018, p. 22-29.
49. MOSCOVITCH, M., HOROWITZ, Y. S. *Thermoluminescent materials for medical applications: LiF: Mg, Ti and LiF: Mg, Cu, P.* Radiation measurements, 41, 2006, p. S71-S77.
50. YAZICI, A. N. *Defect structure of glow peak 1 in LiF: Mg, Ti (TLD-100).* Turkish Journal of Physics, 26(6), 2002, p. 473-482.
51. CHEN, T. C., G. STOEBE, T. *Role of impurities in the thermoluminescence of LiF: Mg, Cu, P*. Radiation protection dosimetry, 100(1-4), 2000, p. 243-246.
52. FREIRE, L., CALADO, A., CARDOSO, J. V., SANTOS, L. M., ALVES, J. G. *Comparison of LiF (TLD-100 and TLD-100H) detectors for extremity monitoring*. Radiation Measurements, 43(2-6), 2008, p. 646-650.
53. OMOJOLA, A. D., AKPOCHAFOR, M. O., ADENEYE, S. O., AWEDA, M. A. *Determination of Calibration Factors and Uncertainties Associated with the Irradiation of MTS-N (LiF: Mg, Ti) Chips with Cesium-137 and X-ray Sources Under Low Doses for Personal Dosimetry in Diagnostic Radiology*. Journal of Global Radiology, 7(1), 2021, p. 4.
54. OGUNDARE, F. O., RAJI, M. N. *Thermoluminescence characteristics of CaF2: Mn irradiated to environmental-like doses*. Journal of Luminescence, 234, 2021.
55. TEXEIRA, M. I., CECATTI, S. G., CALDAS, L. V. *Performance of thermoluminescent materials for high dose dosimetry*. Elsevier, 2008, p. 646-650.
56. DANILKIN, M., LUST, A., KERIKMÄE, M., SEEMAN, V., MÄNDAR, H., MUST, M. *CaF2: Mn extreme dosimeter: Effects of Mn concentration on thermoluminescence mechanisms and properties*. Radiation measurements, 41(6), 2006, p. 677-681.

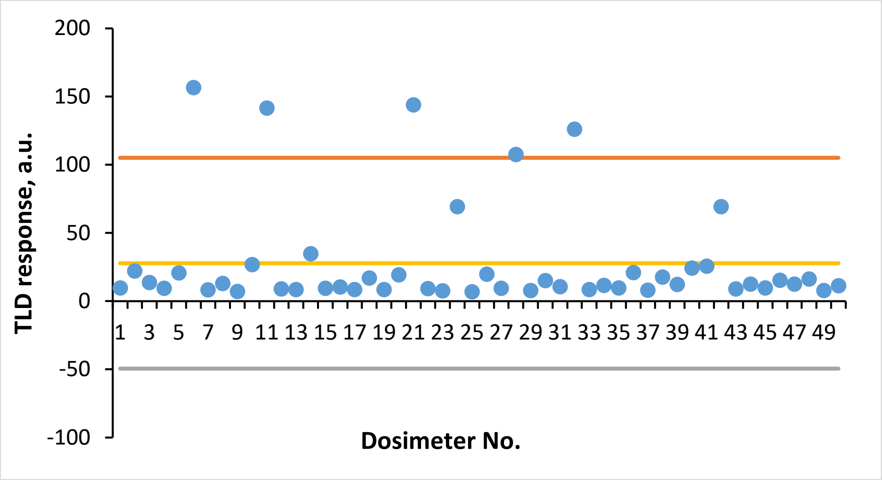
57. YAZICI, A. N., CHEN, R., SOLAK, S., YEGINGIL, Z. *The analysis of thermoluminescent glow peaks of CaF2: Dy (TLD-200) after β-irradiation*. Journal of Physics D: Applied Physics, 35(20), 2002.
58. EL-SAYED, M. A., KAMAL, S. M. *Variation in responce and physical properties of some commercial thermoluminescent dosimeters (TLD-100), CaF2: Dy (TLD-200) and CaSO4: Dy (TLD-900) AFTER GAMMA IRRADIATION*. In The International Conference on Mathematics and Engineering Physics, 2006_.
59. MORADI, F., OLATUNJI, M. A., SANI, S. A., UNG, N. M., FOROUZESHFAR, F., KHANDAKER, M. U., BRADLEY, D. A. *Composition and thickness dependence of TLD relative dose sensitivity: A Monte Carlo study*. Radiation Measurements, 129, 2019.
60. MAIA, A. F., CALDAS, L. V. *Tandem study with thermoluminescent materials in standard diagnostic beams*.International Nuclear Atlantic Conference, 2007.
61. MARTINI, P., BOSCHI, A., CICORIA, G., ZAGNI, F., CORAZZA, A., UCCELLI, L., DUATTI, A. *In-house cyclotron production of high-purity Tc-99m and Tc-99m radiopharmaceuticals*. Applied Radiation and Isotopes, 139, 2018, p. 325-331.
62. NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE. *Molybdenum-99 for medical imaging*. National Academies Press, 2016.
63. ANDERSON, C. J., LING, X., SCHLYER, D. J., CUTLER, C. S. *A short history of nuclear medicine*. In Radiopharmaceutical Chemistry. Springer, Cham, 2019, p. 11-26.
64. ROSS, C. K., DIAMOND, W. T. *Predictions regarding the supply of 99Mo and 99mTc when NRU ceases production in 2018*. ArXiv, 2015.
65. PAPAGIANNOPOULOU, D. *Technetium-99m radiochemistry for pharmaceutical applications*. Journal of Labelled Compounds and Radiopharmaceuticals, 60(11), 2017, p. 502-520.
66. VAN DER BORN, D., PEES, A., POOT, A. J., ORRU, R. V., WINDHORST, A. D., VUGTS, D. J. *Fluorine-18 labelled building blocks for PET tracer synthesis*. Chemical Society Reviews, 46(15), 2017, p. 4709-4773.
67. COLE, E. L., STEWART, M. N., LITTICH, R., HOAREAU, R., SCOTT, P. J. H. *Radiosyntheses using fluorine-18: the art and science of late stage fluorination*. Current topics in medicinal chemistry, 14(7), 2014, p. 875-900.
68. Australian Government. *Production and use of PET radioisotopes. Teacher resource* [online]. ANSTO, 2019, p. 3 [viewed 28 March 2021]. Available from: https://www.ansto.gov.au/media/2291/download
69. YU, S. *Review of 18F-FDG synthesis and quality control*. Biomedical imaging and intervention journal, 2(4), 2006.
70. TECHNOLOGY, N.. *OPERATORS MANUAL for RIALTO*. 1993, Berkshire, England.
71. TAWIL, R. A., PONTIKOS, P. M., VELBECK, K. J., ROTUNDA, J. E. U.S. *Patent No. 5,508,523*. Washington, DC: U.S. Patent and Trademark Office, 1996.
72. WRZESIEŃ, M., OLSZEWSKI, J., JANKOWSKI, J. *Hand exposure to ionising radiation of nuclear medicine workers*. Radiation protection dosimetry, 130(3), 2008, p. 325-330.
73. CARNICER, A., SANS-MERCE, M., BAECHLER, S., BARTH, I., DONADILLE, L., FERRARI, P., VANHAVERE, F. *Hand exposure in diagnostic nuclear medicine with 18F-and 99mTc-labelled radiopharmaceuticals-Results of the ORAMED project*. Radiation Measurements, 46(11), p. 1277-1282, 2011.
74. LEIDE-SVEGBORN, S. *External radiation exposure of personnel in nuclear medicine from 18F, 99mTc and 131I with special reference to fingers, eyes and thyroid*. Radiation protection dosimetry, 149(2), 2012, p. 196-206.
75. COVENS, P., BERUS, D., BULS, N., CLERINX, P., VANHAVERE, F. *Personal dose monitoring in hospitals: global assessment, critical applications and future needs*. Radiation protection dosimetry, 124(3), 2007, p. 250-259.

76. SKOVORODKO, K., BAREIKĖ, M., GUDELIS, A., GRICIENĖ, B. *Occupational exposure in a PET/CT facility using two different automatic infusion systems*. Physica Medica, 2020, p. 169-175.
77. COVENS, P., BERUS, D., VANHAVERE, F., CAVELIERS, V. T*he introduction of automated dispensing and injection during PET procedures: a step in the optimisation of extremity doses and whole-body doses of nuclear medicine staff.* Radiation protection dosimetry, 140(3), 2010, p. 250-258.
78. WRZESIEŃ, M. *The effect of work system on the hand exposure of workers in 18 F-FDG production centres*. Australasian physical & engineering sciences in medicine, 41(2), 2018, p. 541-548.

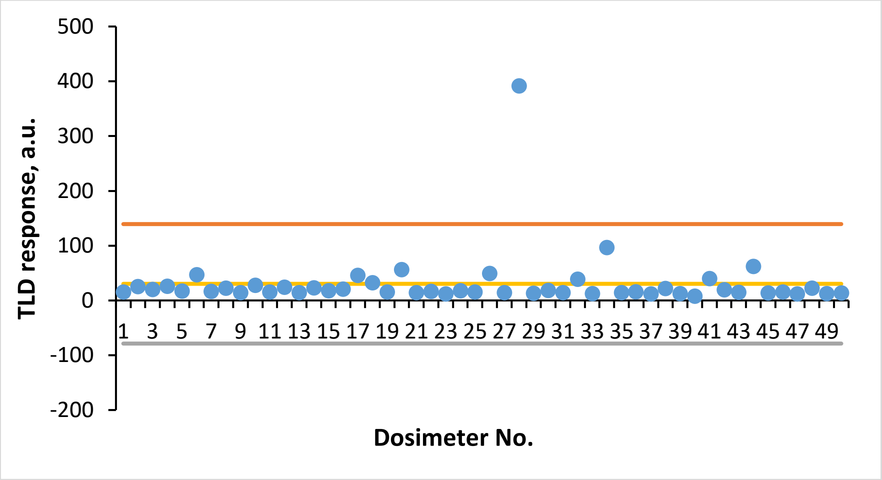
Appendices

Appendix 1. TLDs response distribution after irradiation with ^{99m}Tc radionuclide

0.5 mSv



1 mSv



4 mSv

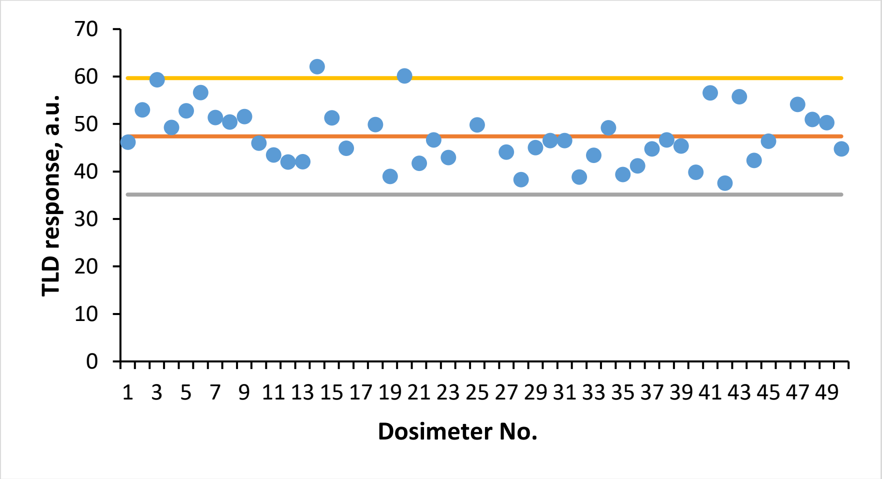


Fig. 35. TLDs response distribution after irradiation with ^{99m}Tc radionuclide (0.5; 1; 4 mSv)

Appendix 2. TLDs response distribution after irradiation with ^{18}F radionuclide

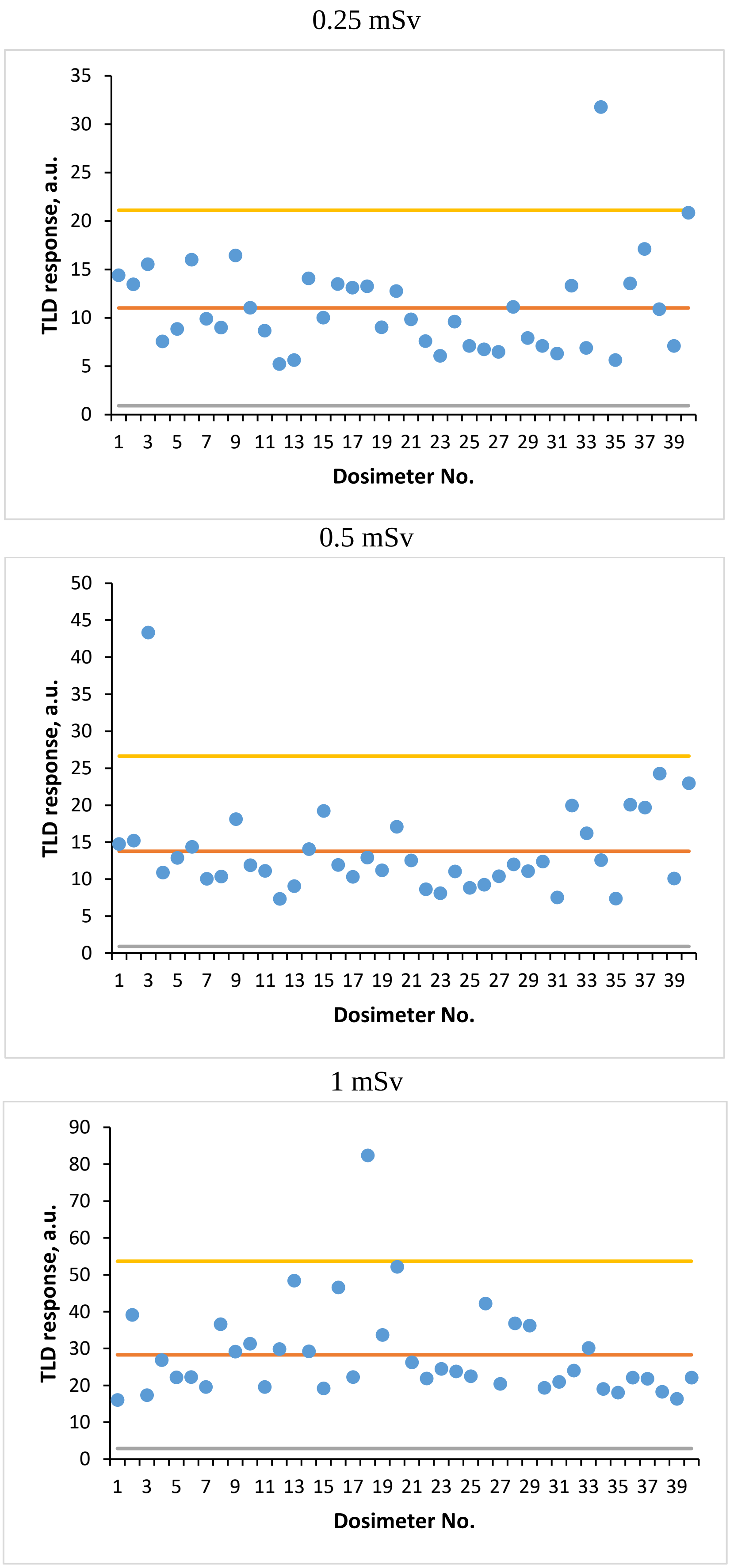


Fig. 36. TLDs response distribution after irradiation with ^{18}F radionuclide (0.25; 0.5; 1 mSv)