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REVIEW ARTICLE

Occupational dose assessment and optimization in PET-CT practice: A review

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ABSTRACT

The combination of Positron Emission Tomography (PET) with Computed Tomography (CT) is an innovative tool for diagnosing, staging, and monitoring various diseases, specifically cancer. Nevertheless, ionizing radiation exposure caused by gamma rays emitting from [^{18}F]FDG may result in substantial iatrogenic effects posing risks to the health and safety of staff members involved in different roles throughout the process. The lack of review articles, comparing discoveries about staff doses and acquiring a deep insight into the potential risks is complicated. To address this issue, this study aims to review various responsibilities and their impact on recorded doses, different organ and environmental dosimetry methods, personnel's annual effective doses, and practical strategies to mitigate exposure risks. Thus, our evaluations are expected to provide fundamental information on these topics. The handling of radiopharmaceuticals and interactions with patients who have received injections are among the most hazardous steps in clinical procedures, significantly impacting occupational exposures. To ensure safety, it is crucial to consider the whole-body effective dose as an important parameter, alongside the dose received by extremities that are in close proximity to radioactive substances. It is worth noting that contrary to expectations, not only does the annual effective dose to different organs of workforces in some medical centers approach the regulatory limits, Moreover, some studies indicate that these doses can exceed safe restrictions. This study aims to review the dosimetry of personnel working with PET-CT and determine the spectrum of the effective doses for diverse organs. Thereafter, effective general and special techniques, such as ALARA principles, are debated to be employed for optimizing radiation doses.

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1. INTRODUCTION

In recent years, owing to ever-increasing diagnostic and clinical applications, the number of PET-CT imaging has experienced a considerable rise in nuclear medicine imaging [1, 2]. While PET/CT scans offer valuable insights into patient health, the ionizing radiation poses risks to personnel. These impacts depend on radiation dose and tissue response, ranging from stochastic effects (like radiation-induced cancers) to deterministic consequences as doses increase. [3, 4]. Although predicting cancer risk in people exposed to doses below 0.1Gy is rather limited by statistical considerations [5], it is nevertheless worth noting that persistent exposure to low-dose radiation may potentially lead to more insidious effects since it is capable of inducing DNA damage and subsequent repercussions, such as carcinogenesis [6-9].

As a formidable technique, PET-CT combines the metabolic data from PET with the anatomical details from CT, making it a powerful diagnostic tool. A standalone PET scan, notwithstanding its effectiveness in detecting metabolic abnormalities, lacks sufficient lucid anatomical localization. On the other hand, conventional CT scans present exhaustive anatomical imagery with sparse data regarding metabolic activity [10, 11]. Combining PET and CT scans merges their complementary aspects into a single image, enhancing cancer detection and staging across various body regions. Furthermore, the implementation of PET-CT is extended to brain imaging, respective to its functionality in revealing metabolic changes associated with neurological conditions in addition to cardiac imaging, also providing valuable data on myocardial perfusion and viability [11, 12]. Consequently, PET-CT has become indispensable in modern radiologic healthcare, offering a comprehensive assessment of a patient's condition.

Localizing a positron-emitting source is the initial step in a clinical PET procedure. This involves synthesizing Fluorine-18 (F-18), a radioactive isotope with a proton-rich nucleus and a half-life of about 109 minutes. In the production process, a cyclotron accelerates protons into Oxygen-18 (O-18) in water as a target material, causing a nuclear reaction that transforms O-18 into F-18 by adding a proton to the nucleus of O-18. Due to the excess of protons in the nucleus, the newly formed F-18 isotope is energetically unstable and undergoes a process called positron emission to attain more stability [13].

A positron, the electron's antimatter counterpart, is emitted from the F-18 nucleus. It carries a positive charge and has the same mass as an electron. The positron travels a few millimeters until it encounters a nearby electron. Immediately after coming into contact, both particles will create what's known as annihilation, in which the particles mutually destroy each other with their combined mass, converting into pure energy in the form of two gamma-ray photons [14].

These gamma rays are emitted in opposite directions, each with an energy of 511 keV. In comparison, Technetium-99m (Tc-99m) used in conventional nuclear imaging emits 140 keV gamma rays. Thus, the radiation in a PET scan is approximately four times higher and more energetically piercing than in conventional nuclear imaging.

High-energy gamma rays from positron annihilation enable accurate cancer detection and depiction of metabolic processes. Simultaneously, a CT scan provides morphological information to precisely localize lesions and abnormalities. With due attention to these capabilities, PET-CT has become a critical tool in the realm of diagnosis [14-16].

During the PET-CT procedure, various steps could exacerbate the staff absorbed dose levels [17]. Notably, staff are exposed to ionizing radiation via the preparation and injection of radiopharmaceuticals. Patients receiving radiotracer compounds then become a source of radiation, making interacting with them a paramount contributory factor. This highlights the importance of the Linear Non-Threshold (LNT) model for radiation effects and the potential adverse health impact of low-dose radiation, where in response, regulatory authorities have established specific limitations to safeguard the health of occupational workers and caregivers [4, 18, 19].

These limitations, recommended by ICRP, include annual limits of personnel equivalent dose, defined as 20 mSv per year averaged over a consecutive 5-year period, with an additional constraint that the amount should not exceed 50 mSv in any year. Furthermore, annual equivalent doses for skin and extremities should not surpass the amount of 500 mSv [20]. Moreover, the IAEA set the annual equivalent dose limit averaged over 5 years at 20 mSv for the eye lenses, with a maximum permissible dose of 50 mSv per year [21]. Therefore, Assessing the equivalent dose of the entire body, eye lens, and extremities of PET-CT staff members is crucial to ensure they do not surpass the recommended annual limits [3, 10, 22]. It is worth pointing out that ICRP and IAEA do not define any limitation for thyroid dose, but with due attention to its radio-sensitivity, it is essential to be evaluated. [23]. These constraints highlight the significance of continuous diligent monitoring of PET-CT staff radiation exposure, implementing strategies to optimize their absorbed dose levels, and ensuring their health and safety in the workplace [3, 19].

Primarily, this study reviews the roles and responsibilities of various PET-CT personnel and their occupational doses. Additionally, it analyzes dosimetry methods and tools for dose measurement to determine the annual effective dose for diverse organs. Ultimately, alongside evaluating the range of critical organs' annual effective dose, it explores general and specific techniques to mitigate radiation exposure risks in PET-CT facilities.

2. PET-CT PERSONNEL AND RESPONSIBILITIES

PET-CT procedures involves numerous tasks that substantially impact the occupational radiation exposure experienced by staff [17]. These tasks are influenced by a wide range of responsibilities, making it essential to understand the absorbed dose for various professionals working within a PET-CT center and their specific roles. Based on the research we focused on four key roles: nurses, medical physicists, technologists, and physicians. While some studies may include additional personnel [24], the absorbed dose for these groups remains minimal due to limited direct interaction with ionizing radiation, making it less of a concern. Consequently, the scarcity of detailed information on other occupations restricts comparisons among all members involved in PET-CT procedures.

To evaluate the dose received by the PET-CT staff, it is important to recognize that the nature of their occupational roles and responsibilities influence their exposure level. Hence, better understanding of these roles is essential for comprehending the extent of the exposure that staff members experience.

2.1. Medical physicists

Occupational roles vary globally, but in PET-CT centers, medical physicists generally have crucial roles in ensuring the safety and efficacy of radiopharmaceuticals by performing diverse and critical tasks particularly as applies to Fluorine-18 Fluorodeoxyglucose [^{18}F]FDG).

Medical physicists are typically responsible for qualitative management of [^{18}F]FDG and can take on various responsibilities for its comprehensive management. This management may include the preparation [22, 24-26], dose calibration and segmentation [26, 27], the radiopharmaceutical activity measurement [28], dispensing [22, 26, 29], and conducing quality assurance checks of the injected radiopharmaceuticals in some centers[16, 22].

Medical physicists possess a deep understanding of performance, limitations, calibration, quality control, regulatory aspects, and image quality assessments of imaging systems. They conduct or oversee daily quality control using calibration sources, such as Germanium-68 phantom and ensure radiation protection during medical exposure. In addition, they are responsible for calibrating dose calibrators and well counters, managing decontamination and waste, and often serving as Radiation Protection Officers (RPO) or Radiation Safety Officers (RSO). Their responsibilities also include handling dosimetry and implementing safety protocols within healthcare settings. A key duty of medical physicists is supervising the PET-CT unit, a responsibility that must be carried with great care [10, 30, 31].

After each injection, medical physicists closely supervise the measurement process of the residual activity remaining in the syringe, which is carried out by technologists. The aim of this practice is to accurately determine the dosage administered to the patient. Additionally, medical physicists can oversee decontamination efforts in the event of spills or contamination, swiftly addressing potential hazards [16, 29].

It should be noted that in most of the research we reviewed, medical physicists carry out the mentioned tasks. However, in some PET-CT centers, it is not uncommon for specific aspects of these responsibilities to be delegated to other trained staff, such as radiochemists or technologists, or even distributed among a team of personnel [1, 25, 28, 32]. For instance, in reference [28], radiopharmacists are responsible for the preparation and transportation of [^{18}F]FDG dose, while in [22], hot lab staff perform the production, labeling, dispensing, and QC testing of radioactive materials. Furthermore, according to AAPM in the United States, medical physicists only supervise the procedure of waste management and daily quality control, which are performed by RSO and technologists, respectively. As a result, they have less contact with radioactive sources, leading to less exposure [33, 34].

Medical physicists' primary source of radiation exposure is their direct involvement in handling radiopharmaceuticals during preparation in hot labs and instrument quality control. The required proximity to radioactive materials during these procedures make them susceptible to radiation exposure. Moreover, their oversight of various phases of the PET-CT procedure may increase their absorbed dose [35].

2.2. Nurses

Among the PET-CT team members, nurses are primarily responsible for patient preparation. Their diverse roles may vary by center but generally include ensuring patients are adequately prepared for imaging. These include checking the patient's fasting status, measuring blood sugar levels, and managing intravenous (IV) lines [15, 28]. While in some medical centers, nurses are responsible for radiopharmaceutical injection [35-37], this role can differ among diverse PET-CT units. In certain facilities, trained nurses administer the radiopharmaceuticals [26] or handle the transfer of the prescribed dose from the hot lab to the injection room [35].

Considering the variety of their duties, the sources of radiation exposure for nurses can differ significantly. Notably, in many centers where trained nurses are responsible for administering injections, this practice often becomes a primary source of radiation exposure [28, 29, 38]. The proximity to radioactive materials during the injection process requires careful management and implementation of effective radiation protection measures.

In many imaging centers where nurses primarily interact with patients who have received radiopharmaceuticals, the primary source of absorbed radiation does shifts to their interactions with these patients [15, 24, 27]. The close contact nurses have with patients who are radioactive (hot patients) contributes to their monthly occupational radiation dose. It is essential to recognize these potential sources of absorbed dose to ensure their safety within this dynamic medical imaging environment. It becomes more critical considering that contrary to technologists and physicists, nurses do not receive any formal education in radiation physics and protection during their nursing training [22, 38]. However, many institutions may choose to conduct periodic training on radiation safety practices for all or some clinical staff.

2.3. Technologists

Technologists are central members of the PET-CT facility-patient interactive team, principally entrusted with patient care during imaging procedures. Similar to nurses and medical physicists, their roles may vary in different institutions but they are commonly responsible for patient escort and positioning [28]. The core responsibility of technologists is to accompany patients from the uptake room to the imaging room and ensure precise positioning on the PET CT scanner bed. However, their roles can differ among centers, technologists sometimes take on additional functions. These tasks may include dose preparation, dispensing [15, 39], administration [16, 23, 31, 40], radiopharmaceutical injection, whether through an auto-injector [16, 27] or manually [22, 39], or even managing all the procedural steps [2, 15].

For technologists, the prominent source of effective dose is their interaction with patients who have received radiopharmaceuticals [32, 40]. The proximity required for patient positioning and care exposes them to substantial ionizing radiation. In centers where they undertake additional responsibilities related to radiopharmaceutical handling, the different amounts of radiation exposure from these materials become an additive factor.

The varied roles of technologists across PET-CT centers underscore the necessity for thorough radiation safety training and strict protocol adherence. Particularly, according to their critical contributions to the imaging process, precise management of technologists' radiation exposure is crucial.

2.4. Physicians

The role of physicians in a PET-CT center is predominantly focused on the interpretation of the PET-CT images, the clinical assessment of patients, and consultation. They analyze the images to identify abnormalities, such as lesions, infections, or other medical conditions, and assess how these findings relate to the patient's medical history, indications, and symptoms [24]. Physicians often communicate their findings and treatment recommendations to the patient and their referring healthcare providers. They may discuss the implications of the PET-CT results, answer questions, and provide guidance on the next steps in the patient's care process [22, 40].

Physicians in a PET-CT center generally have limited radiation exposure compared to other staff [22, 41], and the primary source of their absorbed dose may originate from proximity to patients who have injected radiopharmaceuticals [24]. This exposure can occur during the clinical assessment and consultation phases when physicians interact with patients who have undergone PET-CT imaging. Although the exposure levels for physicians are relatively low compared to staff members directly involved in radiopharmaceutical preparation, administration, and imaging procedures, they still should follow safety protocols to minimize their exposure [1, 40, 42].

3. DOSIMETERS AND MEASUREMENTS

To effectively evaluate the radiation exposure of PET-CT staff and gather essential data, it is imperative to employ specialized tools. Dosimeters are invaluable instruments, allowing us to carefully monitor personnel dose levels and make meaningful comparisons among different staff members to understand their absorbed radiation doses.

Additionally, it is crucial to assess various environmental accumulative doses in a PET-CT center to identify areas where staff may be more vulnerable to radiation exposure, Implementing appropriate protection measures in these areas is essential.

The specific objectives of the assessment determine the selection of dosimeters, each adjusted to distinct positions within the PET-CT facility and calibrated accordingly. In this section, we examine the various types of dosimeters that are strategically positioned and calibrated to fulfill their purpose of quantifying staff exposure to ionizing radiation.

As we explore these essential tools, our aim is to provide a comprehensive overview of their utility and practical features in ensuring the safety and health of PET-CT personnel.

3.1. Ambient dose measurement

Measuring the environmental radiation doses is essential for determining cumulative dose and dose rate in various rooms of a PET-CT unit. It provides valuable information about the radiation exposure that the staff members may encounter. To conduct this assessment, different instruments can be used such as Thermoluminescent Dosimeters (TLDs) [43], Geiger-Muller counters [16] or a combination of both [32]. However, in some studies, electronic dosimeters are preferred for their precision and real-time response [44, 45]. These measurements are typically placed at a height ranging from 1 to 2 meters above the floor [43, 45] in certain areas, such as the uptake room, laboratory, PET-CT examination room, and control room. In the aforementioned areas, dose monitoring is of utmost importance due to the presence of staff members and high dose rate exposure from injected patients and radiopharmaceuticals [16, 32].

3.2. Differences in personal dosimeters

Dosimeters are essential tools for evaluating personnel absorbed radiation doses. To evaluate the staff dose, we should consider the key distinctions between Electronic Personal Dosimeters (EPDs), Thermoluminescent Dosimeters (TLDs), and Optically Stimulated Luminescence (OSL) dosimeters.

3.2.1. EPDs (Electronic personal dosimeters)

EPDs (also sometimes called pocket dosimeters) are active dosimeters that offer real-time assessment of radiation exposure. This particular feature enables us to monitor staff radiation dose at every moment throughout the imaging procedure [15, 31, 44]. Also, this specific capability is instrumental in providing a detailed assessment of radiation exposure at each process step [2, 16, 25, 35]. Furthermore, EPD dosimeters can be set up with an alarm threshold to caution personnel against radiation exposure from injected patients and any possible sources [25, 31].

3.2.2. TLDs vs. OSLs

In contrast, both TLDs and OSL dosimeters are passive dosimeters, necessitate readings by specific readers (e.g. [29, 40]) for a fixed period of time such as one month [25, 28, 42] or three months [1, 23, 37] depending on the inquiry purpose. TLDs offer several advantages, including corrosion resistance, recyclability, minimal fading of readings, an acceptable detection limit, and reasonable sensitivity [15]. OSL dosimeters, on the other hand, exhibit higher sensitivity, up to tenfold, compared to TLDs, which makes them particularly beneficial for personnel working in areas with the risk of low-dose radiation, where detecting lower levels of radiation exposure is essential [38].

3.3. Whole body dosimetry

In nearly all PET-CT centers, whole-body dosimetry is the central variable for comparing and assessing staff radiation exposure (e.g. [1, 42]). The tools predominantly utilized for this purpose include Optically Stimulated Luminescence (OSL: carbon-doped aluminum oxide (Al_2O_3:C)) [38, 40], Thermoluminescent Dosimeters (TLD: LiF: Mg, Ti) [26, 27], Electronic Personal Dosimeters (EPD) [16, 25] and sometimes film badges [2, 32]. These dosimeters are deliberately positioned somewhere between the neck and the waist [40], with common placements in the chest area [23, 26, 42] or within the personnel's pocket [32].

It should be emphasized that to assess whole-body doses effectively, these dosimeters must be thoroughly calibrated. Calibration ensures that they can accurately quantify the equivalent dose at a precise depth of 10 mm below a specific point on the body, known as HP (10) [31, 39]. This calibration process is integral to the reliability and precision of the data collected during staff dose assessment.

3.4. Extremities dosimetry

In many research studies and PET-CT centers, particular attention is devoted to assessing finger doses. This emphasis emerges from the direct interaction of healthcare personnel's hands with radiopharmaceuticals during various procedures [29, 46].

To measure finger doses, Thermoluminescent ring dosimeters (TLD: LiF: Mg, Cu, P) are routinely used [2, 27, 36], whereas the occasional use of Optically Stimulated Luminescence (OSL) dosimeters can also reported [47]. A critical consideration in finger dosimetry is the calibration of these dosimeters, which are modified for measurements at a depth of 0.07 mm (HP (0.07)) below the skin's surface [31, 39, 47].

The positioning of these LiF dosimeters can vary significantly, with placement options including the base of the finger [39, 42], the fingertip [24, 48], or even the wrist [48]. It is remarkable that the choice of dosimeter position can yield significant variations in dose estimates.

For instance, using ring dosimeters on the base of the fingers tends to underestimate finger doses by a factor of 2 to 6 times [27]. Surprisingly, when wristband dosimeters are exploited, dose estimates often register approximately 20 times lower than the most exposed part of the finger [48]. For the most meticulous and precise estimation of finger doses, it is recommended to position dosimeters on the fingertips, the region most directly involved in handling radiation sources [27, 36, 48].

However, it is essential to recognize that variations exist between the dominant and non-dominant hand. The results acquired from these positions demonstrate fluctuation and make it challenging to definitively determine the optimal hand for dosimetry [46, 48]. This current inconsistency reinforces the demand for comprehensive and adaptable finger dosimetry protocols as a means of giving the necessary discernment of the most accurate extremity dose protocol assessment.

3.5. Eye lens dosimetry

In nuclear medicine, due to the proximity to radiopharmaceuticals like [^{18}F]FDG and administered patients alongside the special concentration of international regulations on eye lens dose, the assessment of occupational eye lens dose assumes fundamental importance [49]. However, it is worth noting that in some research studies, this critical aspect has received limited attention.

To attain imperative perception of eye lens dose, Thermoluminescent Dosimeters (TLDs: LiF: Mg, Ti) are the primary tool, and they should be calibrated for measurements at a depth of 3 mm (HP (3)) within the eye lens [24, 36].

Placement of the eye lens dosimeters on the staff is typically carried out on either the forehead [22, 32] or the temple area [24]. It is noteworthy that in some research, the placement on the temple has been suggested as a superior option for precise eye lens dose range assessment [48].

3.6. Other organs dosimetry

In select research studies, there is an added focus on evaluating absorbed doses of specific organs, such as the thyroid [23, 24, 32] and gonads [24]. These assessments play a vital role in improving the comprehension of the radiation exposure experienced by personnel in PET-CT units.

To facilitate the assessment of absorbed doses in these target organs, Thermoluminescent Dosimeters (TLDs) are mainly used [23]. These dosimeters are positioned at the level of each respective organ under investigation [24]. TLDs assist us in ensuring precise and localized measurements, which enable scrutiny of the equivalent dose in these critical anatomical regions.

4. DOSE ASSESSMENT

Assessing radiation doses among healthcare personnel in PET-CT units is critical and intricately linked to their responsibilities. As previously discussed, Staff duties significantly influence their radiation exposure extent. This section explores and compares occupational radiation doses experienced by various groups of workers, with a focus on multiple organs.

Moreover, it is well-established that for practical dose assessment, a meticulous comparison and quantification of both whole-body radiation exposure and the doses absorbed by the most irradiated organs are imperative [21]. By inspecting these vital aspects, we obtain valuable insights into occupational radiation exposure within PET-CT centers. This information helps develop comprehensive strategies for staff protection and safety, ensuring accurate diagnosis while maintaining welfare of healthcare professionals.

In assessing staff radiation doses within PET-CT centers, aligning our findings with established radiation safety standards is crucial. As defined by the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA), these standards set the benchmark for occupational radiation exposure

[21]. For healthcare personnel, the annual limits of effective dose are outlined at 20 mSv per year, averaged over a consecutive five-year period, with the significant stipulation that it should not exceed 50 mSv in a single year. These standards outline specific annual limits: 20 mSv for eye lenses, 20 mSv for the thyroid, and 500 mSv for extremities. Adherence to these standards is essential for protecting staff well-being and maintaining accuracy and safety of PET-CT imaging practice.

4.1. Medical physicists' dose

Studies recorded that the duration of contact with radioactive sources (radiopharmaceuticals and administered patients) for medical physicists is approximately 2 to 5 minutes per scan [28, 35]. In some PET-CT centers, they receive the highest absorbed dose among all staff members [26]. Their exposure to ionizing radiation is influenced by various factors, including workload, specific responsibilities, and individual parameters.

4.1.1. Whole body dose

The whole-body effective dose for medical physicists can vary significantly, ranging from approximately 0.49 [38] to 3 mSv [22]. However, in some research studies [37], their doses have exceeded even 5.62 mSv per year. This variation is a testament to the complex interplay of factors that contribute to radiation exposure, including the demands of their workload and workflow [35].

4.1.2. Extremities dose

Medical physicists' extremities, particularly their hands, can also experience notable variations in absorbed dose, fluctuating from 0.95 mSv [1] to 440 mSv [29]. Surprisingly, in some instances, extremity annual effective doses have approached the ICRP annual limit for finger dose, which is set at 500 mSv. For instance, in references [50] and [29], medical physicists assumed the responsibility for radiopharmaceutical dose fractioning and dispensing. As a result, their extremity annual effective doses reached substantial levels, registering at 422.49 mSv and 484 mSv, respectively.

4.1.3. Eye lens dose

Data regarding the annual effective dose to the eye lens for medical physicists remain somewhat scarce. Some research studies have indicated that the eye lens dose for radiopharmacists in a nuclear medicine center can potentially reach up to 4.67 mSv per year [50]. This finding stresses the need for more accurate research and attention to protecting the eye lens in the context of medical physicists' radiation exposure. It is noteworthy that in reference [51], an estimation suggests that the annual value for Hp (3) during [^{18}F]FDG quality control procedures can be as high as approximately 61 mSv per year, which is a 3-fold annual limit. These figures demonstrate the importance of enhanced safety measures and vigilant eye lens protection for medical physicists, especially during handling radiopharmaceuticals.

4.2. Nurse dose

Nurses have a crucial role in the PET CT process, particularly in administering radiopharmaceuticals. Due to their involvement in the injection process, the annual effective dose incurred by nurses, especially in their extremities, demands careful consideration. It is documented that they are usually in contact with radioactive sources for 50 seconds [32] to 1.21 minutes [28]. It is also reported that their contact time could be prolonged up to 4 to 10 minutes per procedure [35].

4.2.1. Whole body dose

The whole-body annual effective dose for nurses typically stands within a range of approximately 0.16 [1] to 2.5 [22] mSv. However, this range can vary depending on their specific responsibilities. In some cases, the annual effective dose may increase to as much as 3.98 mSv [37] or decrease to 0.01 mSv [36]. These fluctuations are influenced by factors such as the number of injections performed, and safety protocols implemented.

4.2.2. Extremities dose

Nurses' extremities dose per year typically spans from 0.14 [1] to 25.26 mSv [28]. However, when nurses assume responsibility for the injection process, this dose can significantly increase, reaching as high as 185 mSv per year [29]. Hence, it is imperative to implement meticulous safety measures and protective practices during radiopharmaceutical administration.

4.2.3. Eye lens dose

The average annual effective dose range for this group of workers is reported to be 0.15 mSv [36] per year. This dose assessment is particularly crucial, considering close proximity of the eye lens to the radiopharmaceutical, during the [^{18}F]FDG injection process[51]. The estimated value for Hp (3) can reach as high as 52 mSv per year.

4.3. Technologists dose

In many cases, their annual effective dose is the highest among staff members [23, 25, 39], highlighting the significance of their responsibilities and the potential risks associated with radiation exposure. The reported exposure time for technologies varies from 39 seconds [32] to 39 minutes [28] in a single scan. Additionally, the duration recorded in [35] indicates that the staff were in contact with radioactive sources for 10 to 20 minutes during each procedure.

4.3.1. Whole body dose

The annual whole body effective dose for a technologist typically ranges from 0.07 [1] to 7.22 [37] mSv. However, this range can exhibit notable variations. In some instances, effective doses may drop to as low as 0.07 mSv [1] per year, while in other cases, they may rise to as much as 9.1 mSv [15]. These variations can be attributed to factors such as workload and the effectiveness of safety measures.

4.3.2. Extremities dose

The extremities' annual effective dose for technologists is an important consideration, as it can not only reach levels close to the annual allowable limits, such as 444 mSv [27], but also surpass these limits, reaching up to 676 mSv [23] when technologists, due to the lack of facilities, have an inordinate interaction with radiopharmaceuticals. However, these variations are often influenced by workload and the effectiveness of radiation protection protocols [23]. Typically, the average effective extremities dose for technologists ranges from 1.8 [22] or 0.316 mSv [32] to 125 mSv [29] per year.

4.3.3. Eye lens dose

In most instances, the average annual effective dose to the eye lens for technologists is negligible, typically not exceeding 1 mSv [32]. However, there have been instances where the eye dose during nuclear procedures has reached as high as 1.37 mSv per year [50]. This suggests that, while their overall radiation exposure can be substantial, the eye lens is generally shielded from significant radiation.

4.3.4. Thyroid dose

The assessment of thyroid dose among technologists show a wide range of results, ranging from 0.256 mSv [32] to 1.7 mSv per year [23]. These variations highlight the effectiveness of thyroid protection, but it is important to conduct comprehensive monitoring to ensure the health and safety of personnel.

4.4. Physicians' dose

Physicians routinely record the lowest annual effective dose among staff members at PET-CT centers [40]. This lower dose can be attributed to their limited interaction with radiopharmaceuticals compared to other healthcare professionals in the unit.

4.4.1. Whole body dose

The average whole-body annual effective dose for physicians is estimated from 0.15 [38] up to 1.75 mSv [1]. The reduced exposure to ionizing radiation is primarily due to their roles within the healthcare setting, leading to comparatively lower average annual effective dose.

4.4.2. Extremities dose

The typical annual extremities effective dose for physicians is usually around 1.2 mSv [22]. However, according to some studies [1], it has been demonstrated that this dose could potentially increase to as much as 1.80 mSv. Tables 1, 2 and 3 present the average whole-body, extremities, eye lens and thyroid effective doses for various occupational groups per year. This data illustrates the spectrum of effective annual doses, offering insight into the upper limits as evidenced by the maximum reported doses within each group.

5. DOSE OPTIMIZATION

5.1. Dose intensifier factors

In preparation for optimization strategies and solutions, it is imperative to thoroughly examine the factors that considerably contribute to staff absorbed dose, as they have a profound impact.

One pivotal factor, as discerned through the meticulous analysis of studies [22] and [35], is the average activity of administered radiopharmaceuticals. This variable directly influences staff absorbed dose, establishing a clear cause-and-effect relationship. Evidently, any increase in the average activity of administered radiopharmaceuticals results in higher exposure levels while handling these substances. Consequently, this surged exposure leads to a higher absorbed dose for healthcare personnel.

The second factor is the workload. The relationship between workload and radiation exposure in PET-CT centers is intricate and demands more attention. Research findings, such as those in [23], expressly demonstrate that an increased workload corresponds to a notable rise in staff absorbed dose. This correlation describes the workload as a necessity in shaping radiation exposure levels.

The workload for each healthcare worker in a PET-CT center is elaborately linked to two key variables:

1) Patient Volume: The workload correlates directly with the number of patients the center serves. An upsurge in patient numbers inevitably results in increased responsibilities for staff members.

Table 1. Average annual whole-body effective dose (Hp (10)) in mSv

Study	Injection method	Medical physicists	Nurse	Technologists	Physicians	Workload
[28]	Manual injection	1.280	-	2.120	-	17.5 Pt./Mo
[22]	Automatic injection	2.900	3.200	2.400	1.300	30 Pt./Day
[35]	Manual injection	2.040 Max. 2.560	2.350 Max. 2.928	1.940 Max. 2.372	-	100 Pt./Mo (3 groups)
[32]	Automatic injection	-	-	3.710	-	7 Pt./Day
[16]	Automatic injection	-	-	5.000	-	6-9 Pt./Day
[37]	No information	EPD: 4.990 Max. 5.640	3.480 Max. 4.000	6.550 Max. 7.280	-	4-15 Pt./Day (3 centers)
		TLD: 4.945 Max.5.620	3.460 Max. 3.980	6.500 Max. 7.220		
[15]	Automatic injection	-	-	4.7 Max. 9.1	-	27-28 Pt./Day
[1]	Automatic / Manual injection	-	0.590 Max. 1.300	1.630 Max. 5.410	0.830 Max. 1.750	22 Pt./Day
[25]	Manual injection	-	-	Max. 1.840	-	No information
[38]	Manual injection	0.695 Max. 0.830	1.395 Max. 1.660	1.400 Max. 3.270	0.575 Max. 0.740	No information

EPD: Electronic personal dosimeters
TLD: Thermoluminescent dosimeters

Table 2. Average annual extremities effective dose (Hp (0.07)) in mSv

Study	Injection method	Medical physicists	Nurse	Technologists	Physicians	Workload
[24]	Manual injection	Max. 46.7 – Index (R)	Max. 106 - Middle(R) Max. 103 – Thumb (L)	-	-	3 Pt./Day
[28]	Manual injection	410.04	25.26	6.72	-	17.5 Pt./Mo
[22]	Automatic injection	-	2.60	1.80	1.20	30 Pt./Day
[32]	Automatic injection	-	-	0.316	-	7 Pt./Day
[29]	Manual injection	440.01 Max. 484.7	115.80 Max. 185.33	94.83 Max. 125	-	4-15 Pt./Day (3 centers)
[27]	Automatic injection	-	-	Max. 444 - Thumb (R)	-	7 Pt./Day
[23]	Manual injection	-	-	Max. 676 – Index (R)	-	2-14 Pt./Mo (7 centers)
[15]	Automatic injection	-	-	20.4 Max. 118.8 – Ring dosimeter	-	7-28 Pt./Day
[1]	Automatic / Manual injection	2.26 Max. 3.19	0.61 Max. 1.67	5.34 Max. 5.82	0.89 Max. 1.80	22 Pt./Day
[39]	Automatic / Manual injection	-	-	Max. 234 – TLD Ring dosimeter	-	11 Pt./day

Table 3. Average annual eye lens and thyroid effective dose (Hp (3)) in mSv

Study		Staff	Thyroid dose	Eye lens dose		Workload
[32]	Automatic injection	Technologists	0.256	0.262		7 Pt./Day
[51]	Manual injection	Medical physicists	-	10 (Max. 61) – Eye (R)[1] 14 (Max. 53) – Eye (L)	6 (Max. 12) – Eye (R)[2] 6 (Max. 14) – Eye (L)	No Information
		Technologists[3]		5 (Max. 14) – Eye (R) 5 (Max. 9) – Eye (L)		
		Nurse		10 (Max. 52) – Eye (R) 9 (Max. 20) – Eye (L)		
[23]	Manual injection	Technologists	Average dose among seven centers <1.4 Max. 1.7	-		2-14 Pt./Mo In 7 centers
[24]	Manual injection	Medical physicists	0.241	0.153 – Right eye 0.100 – Left eye		3 Pt./Day

[1] During the quality control process
[2] During $[^{18}F]$FDG production
[3] During $[^{18}F]$FDG administration

2) Staff Numbers: By contrast, the workload demonstrates an inverse relationship with the number of workers available. When fewer personnel are available to share the responsibilities, each assumes a more substantial workload.

Recent years have experienced a rapid rise in the number of patients seeking PET-CT imaging, which has amplified the workload placed on healthcare professionals in these settings [2]. Research, such as that outlined in [1], accentuates the consequences of decreased staff numbers, resulting in a heightened workload for the remaining workforce.

The third intensifier element relies on the patient's characteristics. It is worth noting that patients' age and condition can influence the workload level during imaging procedures, subsequently affecting the radiation dose experienced by staff members. Older patients [32], Pediatric Patients [2], and non-ambulatory patients [16], due to potential mobility limitations or additional medical needs, often necessitate more extensive assistance and care throughout the imaging process, which inadvertently results in increased workload and radiation exposure for staff members involved in their care.

When considering gender-related disparities in annual effective doses within the field of radiation protection for PET-CT staff, an intriguing observation emerges. Studies [27] and [15] highlights an interesting and notable trend: female PET-CT unit workers tend to exhibit higher annual effective doses compared to their male counterparts.

The fourth factor, gender-based contrast in absorbed doses among staff members, deserves further exploration and analysis by researchers. The underlying factors contributing to this phenomenon demand scrutiny and consideration. A comprehensive understanding of the existing dynamics may lead to targeted interventions and strategies to mitigate these disparities.

5.2. ALARA principles

The ALARA principles are paramount in optimizing dose in any profession that involves exposure to radiation. Before focusing on dose optimization in PET-CT imaging, it is important to understand these foundational principles. To guide this crucial endeavor in radiation safety, the ALARA principle, an acronym that stands for "As Low As Reasonably Achievable", enables us to minimize radiation exposure while preserving the quality and efficacy of diagnostic imaging.

ALARA embodies a commitment to avoiding unnecessary radiation exposure, emphasizing that any exposure should be justifiable and provide a direct benefit to the individual or patient involved. In PET-CT imaging, the ALARA principles [21] manifest through a triad of fundamental tenets, each designed to reduce radiation exposure systematically. This section explores these principles in-depth and defines the practices that empower healthcare professionals to achieve the delicate balance between accurate diagnostics and minimizing radiation exposure.

5.2.1. Time

In the sphere of PET-CT scan radiation protection, the concept of time holds a dual significance, each contributing to the overall goal of minimizing radiation exposure:

1) The first facet emphasizes the importance of spending as little time as possible near radioactive sources, either radiopharmaceutical materials or patients injected with such agents. Reducing the duration of exposure directly translates to lower cumulative radiation doses for staff members. For instance, utilizing automated and semi-automated injectors has proved that reducing the time spent near [^{18}F]FDG during dose infusion results in less exposure to staff members [47].
2) Additionally, it is crucial to consider the time-dependent aspect of exposure. With the use of [^{18}F]FDG, which has a relatively short half-life, exposure dose rates from injected patients decrease over time [16, 50]. This decrease in radiation exposure is directly tied to the elapsed time since injection. Consequently, minimizing interaction with patients during the critical early moments post-injection becomes advisable when exposure levels are at their highest [45].

5.2.2. Distance

The concept of distance is the next critical factor in the pursuit of radiation protection within PET CT centers. It adheres to a fundamental principle in radiation physics, the inverse square law, which states that the dose received by an organ is inversely proportional to the square of the distance from the radiation source.

Through meticulous research, as demonstrated in studies [16, 44], and [52], we can observe a compelling trend: an increase in distance from an injected patient results in a notable decrease in the dose rate. This empirical evidence highlights the importance of distance in reducing radiation exposure. This finding is highly significance for healthcare professionals working in the PET-CT unit. To efficiently minimize radiation exposure, it is essential to maintain a safe distance from radioactive sources, including radiopharmaceutical materials and recently injected patients. Therefore, staff can proactively reduce exposure levels and create a safer working environment without compromising diagnostic accuracy.

5.2.3. Shielding

Shielding plays a crucial role in reducing radiation exposure for healthcare personnel in PET-CT centers. This fundamental technique acts as a barrier that effectively blocks the passage of ionizing radiation, protecting the well-being of those near radiation sources. In PET-CT centers, shielding assumes various forms and is employed strategically. One notable example is the use of tungsten-shielded syringes for radiopharmaceutical injections [24, 28]. These specialized syringes not only prevent radiation leakage but are often transported within lead containers to enhance their shielding capabilities [29, 35]. Research [23] has demonstrated, the critical importance of shielding. The removal of syringe shields can lead to additional absorbed doses for personnel. However, the role of additional shielding within PET-CT units, such as lead aprons and glasses, is still a matter of debate and scrutiny. Research [28] and [29] highlight instances where supplementary shielding measures are used [53], others suggest that added shielding against exposed gamma rays from [^{18}F]FDG may yield negligible benefits.

5.3. PET-CT specific techniques

As shown in the study [54], implementing weight-based FDG dose adjustments is an effective strategy to reduce staff radiation exposure. By enhancing the injected dose based on patient weight, there has been an 11% reduction in radiation dose. This approach not only benefits patients, but also minimizes staff exposure during radiopharmaceutical preparation, injection, and patient handling. Additionally, it improved image quality in certain weight groups, making it a suitable approach for dose optimization in PET/CT centers.

The study [55] also recommends systematic staff rotation and workload sharing. It argues that careful planning, which ensures dose distribution among operators alongside adequate training in radiopharmaceutical handling, can effectively optimize occupational effective and equivalent doses. Furthermore, personalized dosing rather than a fixed amount can lower both patient and personnel exposure in a cost-effective manner.

Utilizing an e-controlling system as a cutting-edge technique is introduced in the study [56] resulting in a 61.2% reduction in the annual dose for operators. It is demonstrated that compared to manual dispensing, remote-controlled radiopharmaceutical loaders and dispensers can drastically lower the radiation dose experienced by staff. Therefore, this method represents an outstanding feature for minimizing occupational dose in PET CT centers.

5.4. Other techniques

In the following discussion, we consider specific potential solutions and various strategies to reduce the influence of the mentioned factors on the absorbed dose. Recommendations include the employment of additional or “traveling” per diem staff to distribute specific responsibilities, allowing each worker to manage a more attainable workload [29, 32]. Alternatively, healthcare professionals can adopt a rotational approach, enabling them to change responsibilities [24] or rotate among different imaging units within a center [16]. Such strategic systems focus on reducing the frequency of interactions with [^{18}F]FDG, thereby promoting a safer working environment for staff.

Experience and skill during the PET-CT imaging procedure also emerge as decisive determinants in optimizing radiation exposure for the personnel. Research studies [23] and [36] provide valuable insights into the indispensable impact of worker experience on absorbed doses, often revealing that less experienced personnel may unintentionally contribute to elevated radiation exposures. However, a promising aspect lies in proactive training and skill development. It becomes conspicuous that many of these errors can be prevented by implementing targeted periodic training programs and cultivating hands-on expertise [22]. Nevertheless, a study[2], contradicts to the expectations, finding that increase in the staff experiences does not affect the absorbed dose, which it remains constant over the research time.

Another critical factor exacerbating radiation exposure to the staff members is the transportation of [^{18}F]FDG from the hot lab to the injection room [52]. As debated previously, the less handling of radioactive sources leads to lower radiation dose. Hence, sometimes, adjusting the layout of the PET-CT unit accelerates the transferring process and subsequently reduces staff radiation dose. In [31], the installation of a new transportation port between the hot cell and injection room significantly reduces the effective dose received by personnel. This new port provides a more efficient and faster method for transporting [^{18}F]FDG, decreasing the need for extensive handling of radioactive materials.

The final and notably impactful step for dose optimization in a PET-CT unit involves the utilization of semi-automatic or fully automatic injectors. As evidenced in research studies [35] and [47], the implementation of auto-injectors has demonstrated their remarkable effectiveness in reducing staff exposure. By minimizing direct contact between staff and radioactive materials, there is a notable reduction in both extremity and whole-body radiation doses. In principle, using auto-injectors proves particularly advantageous in high-workload PET-CT centers, which significantly decrease radiation doses for staff, specifically during preparation and administration of [^{18}F]FDG.

CONCLUSION

This study reviews the dosimetry of PET-CT personnel and determines the spectrum effective dose across various organs. The study suggests that optimizing radiation dose in PET-CT imaging requires a multifaceted approach that addresses different factors contributing to staff absorbed dose. The average activity of radiopharmaceuticals used, workload, patient characteristics, and gender differences all play important roles in setting radiation exposure levels for healthcare personnel. Following the ALARA principles pertaining to time, distance, and shielding is essential for reducing radiation exposure while retaining diagnostic accuracy. Additionally, strategies such as workload distribution, implementation of rotating techniques, training programs, and the use of semi-automated or fully automated injectors have also shown effectiveness in lowering absorbed doses for staff. By employing these strategies and addressing specific challenges encountered in PET-CT centers, healthcare personnel can create a safer working environment and enhance radiation protection for both themselves and their patients.

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