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Occupational radiation dose assessment across clinical specialties in a Nigerian tertiary hospital using optically stimulated luminescence dosimetry

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Abstract

Occupational radiation exposure varies across healthcare specialties, requiring monitoring. This study assessed occupational radiation exposure among healthcare workers (HCWs) at the National Hospital Abuja (NHA), Nigeria, using optically stimulated luminescence (OSL) dosimetry. A total of 386 annual OSL dose records (worker-years) (2020–2024) were analyzed across diagnostic radiology, nuclear medicine, radiotherapy, and medical physics departments to determine personal dose equivalents (Hp (10), Hp (3), and Hp (0.07)). A single chest-level badge was worn over the lead apron; consequently, Hp (3) and Hp (0.07) represented chest-level estimates rather than dedicated eye-lens or extremity measurements. Year-stratified comparisons characterized dose distributions. Technologists recorded the highest mean annual doses of 0.92, 0.93, and 0.93 mSv for Hp (10), Hp (3), and Hp (0.07), respectively, with means strongly influenced by a single 46.12 mSv record (median Hp (10): 0.21 mSv). Darkroom technicians had the lowest exposures. Pooled median Hp (10) was highest in nuclear medicine (0.54 (IQR 0.40) mSv), followed by radiotherapy (0.47 (IQR 0.68) mSv), medical physics (0.40 (IQR 0.76) mSv), and diagnostic radiology (0.07 (IQR 0.20) mSv); significant interdepartmental differences occurred only in 2024. The 46.12 mSv record exceeded the 20 mSv annual average effective-dose limit but remained below the 50 mSv single-year ceiling under the five-year framework and requires verification. All other reported Hp (10) and Hp (3) values were below 20 mSv, and Hp (0.07) values were below the 500 mSv annual skin-dose limit. Findings indicate generally low occupational exposure and support OSL dosimetry for routine monitoring in resource-limited healthcare settings.

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1. Introduction

Ionizing radiation is widely used across multiple sectors, with its most critical application in healthcare, where it supports diagnostic imaging, interventional procedures, and cancer therapy [1]. Advances in medical technology, coupled with rising healthcare demands and an aging population, have significantly expanded the use of radiation-based procedures globally [2]. Consequently, occupational exposure among healthcare workers has increased, making radiation protection a global concern [3]. A study by Liu *et al.* [4] confirmed that although doses are generally within regulatory limits, cumulative low-dose exposure remains associated with potential long-term health risks, including stochastic effects such as cancer.

To mitigate these risks, international bodies such as the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) provide comprehensive radiation protection guidelines, including dose limits, monitoring protocols, and exposure optimization [5]. Occupational exposure to ionizing radiation varies across clinical specialties due to differences in procedures, workloads, exposure conditions, and radiation protection practices. In Nigeria, inadequate personnel monitoring, inconsistent dosimeter use, and incomplete dose records remain concerns in tertiary healthcare institutions [6]. Existing studies have largely focused on selected professional groups or individual facilities, leaving limited comparative evidence across multiple clinical specialties [6–8]. At the National Hospital, Abuja, this evidence gap limits the identification of occupational dose variations and the implementation of targeted radiation protection measures. Recent international reports highlight ongoing efforts to strengthen radiation safety frameworks and improve dosimetric practices in medical settings [9, 10].

Monitoring occupational radiation exposure is essential for regulatory compliance, early detection of abnormal exposures, and support for optimization strategies, including the ALARA (As Low As Reasonably Achievable) principle. It also provides critical data for long-term health surveillance and for identifying high-risk procedures or departments. Contemporary studies show that exposure levels vary across clinical specialties, with higher doses often observed in nuclear medicine and interventional practices, underscoring the need for continuous, specialty-specific monitoring [11–13]. In Nigeria, recent investigations likewise emphasize the need for sustained monitoring and improved radiation protection practices in tertiary healthcare facilities [14].

Among available dosimetry techniques, optically stimulated luminescent dosimeters (OSLDs) have become a preferred tool for personnel monitoring because of their high sensitivity, stability, reusability, and ability to accurately measure low-dose exposures. Their advantages over traditional methods, such as film badges and thermoluminescent dosimeters, make them well suited for long-term occupational dose assessment [15]. Recent longitudinal studies have demonstrated the effectiveness of OSL dosimetry in capturing occupational exposure trends across medical specialties, further supporting its use in routine personnel monitoring [16].

This study evaluates long-term occupational radiation exposure among healthcare professionals across key clinical specialties, including diagnostic radiology, radiotherapy, nuclear medicine, and medical physics, at the National Hospital Abuja (NHA), Nigeria, from 2020 to 2024, a five-year period, using OSL dosimetry. By analyzing dose distributions and temporal trends, the study aims to provide evidence-based insights to enhance radiation protection practices and occupational safety in tertiary healthcare settings. To the best of our knowledge and based on the literature available at the time of this study, this represents the first comprehensive investigation of its kind within the scope of our search.

2. Materials and methods

This study was carried out with healthcare professionals using OSLDs across selected clinical departments, including diagnostic radiology (DR), radiotherapy (RT), nuclear medicine (NM), and medical physics (MP) at the National Hospital Abuja (NHA), Nigeria, from 2020 to 2024 (five years).

The OSLDs consist of cards with holders that contain a detector crystal of Al2O3:C (aluminium oxide doped with carbon) to provide measurements for skin, eye lens, and deep doses. Each worker was issued a single badge worn on the upper-left side of the chest outside (over) the lead apron; no dosimeter was worn at eye level (collar, headband, or spectacles), and no ring or wrist (extremity) dosimeter was issued. The upper-left side of the chest is the most crucial area to wear the dosimeter outside the lead apron, as it is expected to receive the highest radiation exposure. According to EURADOS report (2023), when only an over apron dosimeter is employed, a central position high on the chest is preferable to minimise the dependence on the beam projection. This is particularly true if the dosimeter is also used to provide an estimation of the eye-lens dose. The left side is preferred as a practical convention and for standardization. It also gives a relatively reproducible measurement. Initial readings were obtained using a calibrated Landauer automatic OSLD reader 200A in accordance with the established manufacturer's protocols.

Phase 1: new/raw OSLD chips were optically annealed using a pocket annealer to erase any background radiation. The chips were then read in an in-light reader to ensure the background radiation in the OSLD chips was dropped to a 0.01 mSv baseline. The displayed readings were saved with the following information: the name of the personnel who used the OSLD badge, their department, and the code. The OSLD chips were packaged and sent to the personnel who used them for three months. At the end of the three months, the OSLD chips were returned to the medical physics dosimetry laboratory to be read in the in-light reader. The reader's dose-calculation algorithm derived Hp (10), Hp (3), and Hp (0.07) from the signals of the filtered detector elements of the same chest-worn badge; consequently, Hp (3) and Hp (0.07) refer to the badge position on the chest and not to the eye or the hands.

Phase 2: The chips were calibrated before being deployed as follows: all bleached chips were irradiated to a known dose, e.g., 5 mGy, from calibrated Cs-137. They were then read in the OSL reader to calculate the element correction factor (ECFi), which is stored in the database. This corrects for individual sensitivity. The reader calibration factor (RCF) is obtained by irradiating a set of reference dosimeters that are designated as calibration dosimeters to known doses, e.g., 0, 1, 2, 5, 10, 50 mGy. These were read to create a calibration curve: Count versus Dose. The reader software generates RCF to convert raw counts to dose.

The OSLD reader used for calibration and quality control consists of three components: the optical stimulation unit, the optical filtering and light detection unit, and the built-in QC stability check. The optical stimulation unit includes a blue light source that activates OSLDs previously irradiated, releasing the stored signal. The optical filtering and light detection unit, on the other hand, uses optical filters to select the emission band of blue-UV light while rejecting any stimulation from stray or leaked light. A photomultiplier tube (PMT) in the OSLD reader helps to detect the light. Lastly, the "built-in" QC unit in the reader uses a reference light source inside the reader to check the stability of the detector response and the integrity of the optical pathway [18]. The cumulative doses were expressed in millisieverts (mSv) and analysed for each participant during the five-year period from 2020 to 2024.

Metrological traceability, uncertainty, detection limit and quality assurance. The reference irradiations used to determine the ECFs and the RCF were delivered with Microstar in-light reader with calibration chips known as Landauer, France, whose output was traceable to Primary standard dosimetry laboratory (PSDL) of the National Institute of Standards and Technology (NIST) and Secondary Standard dosimetry laboratory (SSDL) at the National institute of radiation protection and research (NIRPR) Ibadan, Oyo state, Nigeria with calibration certificate number: NNRA/DSP/AUT/ACR/827/2025 dated 5 August 2025. Conversion to Hp (10), Hp (3), and Hp (0.07) used the conversion coefficient of ISO 21909-1:2015. The calibration range used was from 0 mSv to 5000 mSv (5 Sv), covering all recorded annual values. The lower limit of detection of the system was from 0.5 to 0.7 mSv per monitoring period, and readings below it were recorded as 0 mSv.

The expanded uncertainty of 5% is the standard uncertainty of measurement multiplied by the coverage factor (k = 2), which for a normal distribution corresponds to a coverage probability of approximately 95%. The reported annual Hp (10) value was ±5%, combining the calibration, element-correction-factor reproducibility, energy and angular response, fading, and background subtraction. Quality assurance acceptance criteria were: daily reader QC checks (dark count, PMT reference light, and calibration-check dosimeters) within ±5% of their reference values; element correction factors within 0 mSv to 5 Sv range; and overall dosimeter performance within the IAEA accuracy requirement for individual monitoring, i.e., within a factor of 1.5 in either direction at doses near the annual limits and a factor of 2 near the recording level [19].

The dosimeters were then returned to the dosimetry laboratory of the medical physics department at the National Hospital in Abuja, where the dosimeter reading facility is located. A model Landauer automatic OSLD Reader 200A with a computer program was used to evaluate the OSLD's reading. For the years 2020 to 2024, the personal dose equivalents Hp (10), Hp (3), and Hp (0.07), all obtained from the same chest-worn badge, were retrieved from the medical physics department of NHA. Following the 2007 Recommendations of the International Commission on Radiological Protection (ICRP Publication 103), the personal dose equivalent Hp (10) is used as the operational quantity for estimating effective dose in individual monitoring [20]. The OSLDs distributed to personnel were collected during the evaluation of personnel dose equivalents. Readings of OSLDs were performed quarterly. Five non-irradiated OSLDs of the same type as those used to measure personal doses were used to measure the background radiation dose, which was subtracted from the measured dose values.

The OSLD cards were read out on an automated OSLD reader. The calibration of the OSLDs was performed at the dedicated dosimetry laboratory of the Department of Medical Physics of NHA. It is important to mention that a single OSLD badge was recommended for workers wearing lead aprons, except for the nuclear medicine workers, for whom more than one badge was recommended. In our study, a single chest-worn OSLD badge was used for all Healthcare workers, including nuclear medicine staff, and no eye-level or extremity dosimeters were used. Accordingly, the reported Hp (3) is a chest-level estimate of the eye-lens dose obtained from the badge algorithm; it is not equivalent to eye-lens dosimetry performed close to the eye as recommended by ISO 15382 [21] and the IAEA [19], and it may underestimate the lens dose when the head is exposed above the apron, the radiation field is non-uniform, or protective eyewear is worn.

Similarly, the reported Hp (0.07) represents the skin dose at the chest badge position and not the dose to the hands or extremities, which may be considerably higher for staff who prepare and administer radiopharmaceuticals. Pregnant workers were issued a supplementary badge, worn inside the apron at waist level, to monitor the dose to the foetus.

Data collection and analysis procedure: The OSLD dose reports from 2020 to 2024 of HCWs who met the inclusion criteria were retrieved from the radiation safety officer (RSO). The unit of analysis was the individual worker-year, with quarterly dosimetric records aggregated to annual personal dose equivalents and categorized by department, job roles, and year. Monitoring periods recorded in the register as spanning two calendar years (e.g. '2019–2020' or '2023–2024') were assigned to the calendar year in which the period ended, except that the period '2024–2025', which began in the final study year, was assigned to 2024; data-entry errors in the year field (an automatic-fill sequence in 27 consecutive records) were corrected against the record sequence. All 386 records were thus assigned to 2020–2024. One record each lacked an Hp (10), Hp (3), or Hp (0.07) value and was excluded only from analyses of that quantity.

The register was de-identified and did not contain a persistent worker identifier, so records of the same worker in different

years could not be linked. The data were organized in Excel and analysed using Statistical Package for the Social Sciences (SPSS) version 26 for Windows (IBM Corp., Armonk, NY, USA); year-stratified tests and post-hoc comparisons were computed in Python (SciPy 1.18). Continuous variables (Hp (10), Hp (3), and Hp (0.07)) were summarized as mean ± standard deviation or median (interquartile range). Because all three distributions were strongly right-skewed (Shapiro–Wilk $W \leq 0.17$, $p < 0.001$), medians were used for comparisons. As distributional and data-quality checks, the range and 95th percentile were examined, and records exceeding 6 mSv in any quantity (three-tenths of the annual effective dose limit) were flagged for verification; the effect of flagged records on the mean was assessed by recalculating the mean without them (Table S1). Statistical significance was set at $p < 0.05$.

Because records could not be linked to individual workers across years, within-worker correlation could not be modelled with repeated-measures, mixed-effects, or generalized estimating equation methods. Instead, every inferential comparison was restricted to a single monitoring year, in which each worker contributes only one aggregated annual record. Kruskal–Wallis tests were therefore performed separately for each year (year-stratified), comparing job categories within each department and comparing departments with each other; groups with fewer than three records in a given year were excluded from the tests. Where a Kruskal–Wallis test was significant, pairwise comparisons were made with Dunn's test [22], with p-values adjusted for multiplicity using the Holm method [23]. Medians and IQRs pooled over 2020–2024 (Tables 2 and 3) are presented descriptively, and no p-values are reported for pooled data. Median occupational radiation dose values were used to plot temporal trends and dose variations over the study period to examine potential increases or decreases in exposure levels. Regression analysis was not employed.

The protection quantities absorbed dose (D), equivalent dose (HT), and effective dose (E) are defined below for reference only. They were not measured directly; the quantities reported in this study are the operational personal dose equivalents Hp (10), Hp (3), and Hp (0.07).

2.1. Dosimetric calculations and equations

2.1.1. Absorbed dose (D, gray (Gy))

The absorbed dose is defined by Eq. (1):

$$D = \frac{\mathrm{d}\varepsilon}{\mathrm{d}m}, \tag{1}$$

where $\mathrm{d}\varepsilon$ and $\mathrm{d}m$ indicate the energy imparted (J) and mass (kg), respectively.

2.1.2. Equivalent dose (H_T, sievert (Sv))

The equivalent dose is defined by Eq. (2):

$$H_T = \sum_R \omega_R D_{T,R}, \tag{2}$$

where ω_R is the radiation weighting factor (1 for X-rays/gamma radiation).

2.1.3. Effective dose (E)

The effective dose is defined by Eq. (3):

$$E = \sum_T \omega_T H_T, \tag{3}$$

where ω_T is the tissue weighting factor and H_T is the equivalent dose to tissue T.

3. Results and discussion

3.1. Distribution of OSLDs by department

Analysis was conducted on 386 annual OSL dose records to obtain the occupational radiation exposures of healthcare workers in the selected departments, as shown in Table 1. This presents the mean occupational radiation dose (± standard deviation) for Hp (10), Hp (3) (chest-level estimate of the eye-lens dose), and Hp (0.07) (skin dose at the chest badge position) across different job categories and departments. The distribution of the healthcare workers is as follows: medical doctors/oncologists (DR), n = 135; radiography technologists (RT), n = 128; registered nurses (RN), n = 42; radiopharmaceutical pharmacists (RP), n = 6; medical records (MR), n = 6; health attendants (HA), n = 10; darkroom technicians (DT), n = 3; and medical physicists (MP), n = 56, respectively.

It shows that technologists (RT) have the highest mean radiation exposure: Hp (10) 0.92 ± 4.32, Hp (3) 0.93 ± 4.35, and Hp (0.07) 0.93 ± 4.17 mSv, respectively. However, these means are dominated by a single record of 46.12 mSv; the median Hp (10) for technologists was 0.21 (IQR 0.53) mSv, and excluding the three records flagged above 6 mSv reduced the mean Hp (10) to 0.40 ± 0.61 mSv (Table S1). This finding underscores the fact that technologists work directly in proximity to radiation-emitting machines such as X-ray machines, computed tomography machines and mammography machines. The darkroom technicians have the lowest

Table 1: Mean occupational radiation doses Hp (10), Hp (3), and Hp (0.07) by job title and department in the overall study population.

Overall	N	Hp (10) Mean ± SD	Hp (3) Mean ± SD	Hp (0.07) Mean ± SD
Medical doctors/Oncologists	135	0.43 ± 0.49	0.44 ± 0.50	0.45 ± 0.50
Radiography technologists	128	0.92 ± 4.32	0.93 ± 4.35	0.93 ± 4.17
Registered nurses	42	0.32 ± 0.32	0.33 ± 0.34	0.35 ± 0.36
Radiopharmaceutical Pharmacists	6	0.65 ± 0.18	0.70 ± 0.24	0.74 ± 0.32
Medical Records	6	0.63 ± 0.23	0.68 ± 0.30	0.73 ± 0.38
Health Attendants	10	0.64 ± 0.92	0.64 ± 0.92	0.65 ± 0.93
Darkroom technicians	3	0.09 ± 0.05	0.09 ± 0.05	0.10 ± 0.06
Medical Physicists	56	0.73 ± 0.85	0.73 ± 0.85	0.74 ± 0.86
Total N	386			
Diagnostic Radiology				
Medical Doctors	63	0.21 ± 0.38	0.22 ± 0.38	0.22 ± 0.37
Radiography Technologists	38	1.32 ± 7.47	1.32 ± 7.47	1.30 ± 7.19
Registered Nurses	4	0.13 ± 0.13	0.13 ± 0.13	0.16 ± 0.15
Health Attendants	5	0.02 ± 0.02	0.02 ± 0.02	0.03 ± 0.02
Darkroom Technicians	3	0.09 ± 0.05	0.09 ± 0.05	0.10 ± 0.06
Nuclear Medicine				
Medical Doctors	12	0.72 ± 0.26	0.78 ± 0.31	0.82 ± 0.37
Radiography Technologists	11	0.56 ± 0.18	0.59 ± 0.24	0.61 ± 0.30
Registered Nurses	14	0.59 ± 0.15	0.63 ± 0.21	0.67 ± 0.28
Radiopharmaceutical Pharmacists	6	0.65 ± 0.18	0.70 ± 0.24	0.74 ± 0.32
Medical Records	5	0.61 ± 0.25	0.67 ± 0.34	0.72 ± 0.42
Radiotherapy/Oncology				
Medical Doctors	60	0.59 ± 0.53	0.61 ± 0.55	0.61 ± 0.55
Radiography Technologists	79	0.77 ± 1.96	0.79 ± 2.01	0.80 ± 2.04
Registered Nurse	24	0.19 ± 0.31	0.19 ± 0.31	0.19 ± 0.31
Health Attendants	5	1.26 ± 0.97	1.26 ± 0.97	1.28 ± 0.99
Medical record	1	0.76	0.76	0.76
Medical physics	56			
Total N	386			

Values are presented as mean ± SD, except as stated otherwise.

mean exposure doses: Hp (10) 0.09 ± 0.05, Hp (3) 0.09 ± 0.05, and Hp (0.07) 0.10 ± 0.06 mSv (Figure 1). The mean doses recorded are consistent with some international reports and lower than others. For instance, in Ghana the mean deep dose was, 1.05 mSv Hasford *et al.* [24], very close to the Ethiopian value [25].

Higher values have been observed in Kenya (~2.15 mSv) and Malawi (~2.96 mSv) [26]. By contrast, studies in China (0.35 mSv) Deng *et al.* [27], Ireland (0.32 mSv) Colgan *et al.* [28], Saudi Arabia (0.41 mSv) Shubayr *et al.* [29], the UAE (0.39–0.83 mSv), and Pakistan (0.29–0.80 mSv) Jabeen *et al.* [30] have reported substantially lower annual doses. These comparisons suggest that Nigerian radiographers' exposures are typical for developing countries with moderate workloads and protections.

3.2. Occupational doses in diagnostic radiology

Radiography technologists exhibited the highest mean Hp (10) in diagnostic radiology, 1.32 ± 7.47 mSv (range 0.00–46.12 mSv). The very large standard deviation is caused by a single annual record of 46.12 mSv (Hp (3) 46.12 mSv; Hp (0.07) 43.82 mSv) from 2021; the remaining 37 technologist records ranged from 0.00 to 1.12 mSv (median 0.05 mSv; 95th percentile 0.53 mSv), and excluding this record reduced the mean Hp (10) to 0.11 ± 0.20 mSv (Table S1). This value is about 40 times higher than any other value in the department and may reflect a badge that was irradiated while not being worn or a recording error rather than a genuine personal exposure. The outcome of the RSO's verification of the 46.12 mSv record was from the dosimeter badge of the radiopharmacist, which was left in the "hot lab." Pending verification, the record was retained in all tables, and medians, which are insensitive to it, were used for comparisons.

Based on medians, technologists (0.05 (IQR 0.09) mSv) did not have higher doses than medical doctors (0.09 (IQR 0.26) mSv) (Table 2), and year-stratified Kruskal–Wallis tests found no significant differences between job categories in either 2020 or 2021 (Table S2). Medical doctors in this department showed comparatively low mean doses (0.21 ± 0.38 mSv), as shown in Table 1 and Figure 2. This result differs from findings from a study indicating that radiation workers in diagnostic radiology receive higher

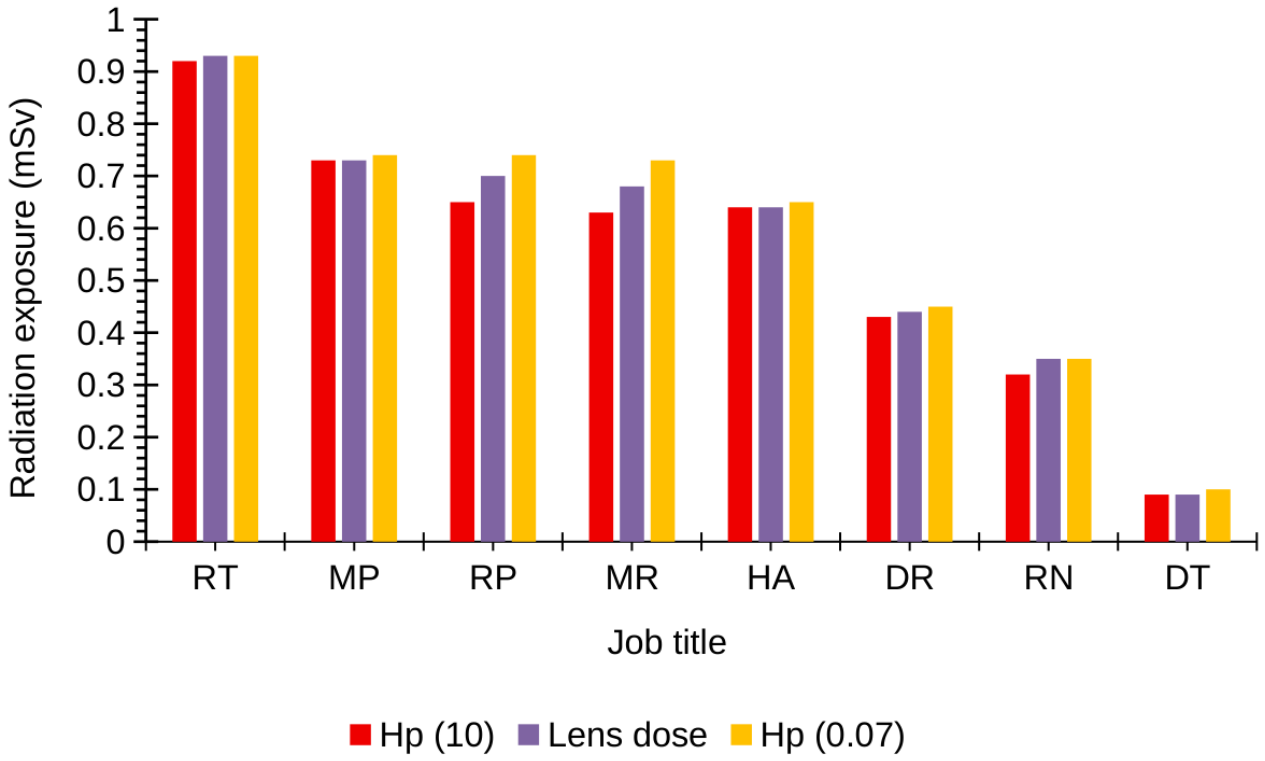


Figure 1: Occupational radiation dose levels by job title in the overall study population. Mean Hp (10), Hp (3), and Hp (0.07) (values as in Table 1). RT = Radiography technologists; MP = Medical physicists; RP = Radiopharmaceutical pharmacists; MR = Medical records; HA = Health attendants; DR = Medical doctors, radiologists and oncologists; RN = Registered nurses; DT = Darkroom technicians.

radiation doses compared to those in other fields [16]. In another study, workers in diagnostic radiology contributed 68% more to the collective effective dose than workers in other fields between 2010 and 2016 [27]. Effective personal monitoring practices and radiation awareness training for staff, especially technologists, should be developed and reinforced annually.

3.3. Occupational doses in nuclear medicine

In nuclear medicine, mean personal dose equivalents were generally higher, ranging from 0.56 ± 0.18 to 0.82 ± 0.37 mSv, compared to those in the radiology department. Medical doctors/oncologists in nuclear medicine department recorded the highest mean personal dose equivalents (Hp (10): 0.72 ± 0.26 mSv; Hp (3): 0.78 ± 0.31 mSv; Hp (0.07): 0.82 ± 0.37 mSv), as shown in Table 1 and Figure 3. Radiography technologists and nurses showed moderate exposure levels, while radiopharmaceutical pharmacists and medical records staff had comparable mean personal dose equivalent values. All nuclear medicine records were from 2024, so each worker contributed one record; the K–W test indicated no statistically significant differences across job categories for Hp (10), Hp (3), or Hp (0.07) ($p = 0.488$, 0.521, and 0.725, respectively; Table S2), suggesting relatively homogeneous exposure patterns within this department.

Our results did not align with the study by Nassef & Kinsara [31], which noted that, generally, nuclear medicine technicians received relatively higher chest absorbed doses (> 2 mSv), and annual effective skin doses to the fingers ranged from 12.88 to 31.7 mSv, due to their primary responsibilities of carrying out examinations according to the given protocol; finger doses were not measured in the present study, so these values are not directly comparable with our chest-level Hp (0.07). However, the measured values were well below the dose limit. In another study, Alakhras *et al.* [11] also noted that nuclear medicine technicians received relatively higher effective dose values of 0.58 to 0.85 mSv than other healthcare workers. These results underscore the need for regular personal dosimetry monitoring, periodic training, and enforcement of the national and international radiation safety guidelines for nuclear medicine staff and other radiation workers.

3.4. Occupational doses in radiotherapy

Table 1 and Figure 4 reveal that technologists in the radiotherapy/oncology department received higher mean personal dose

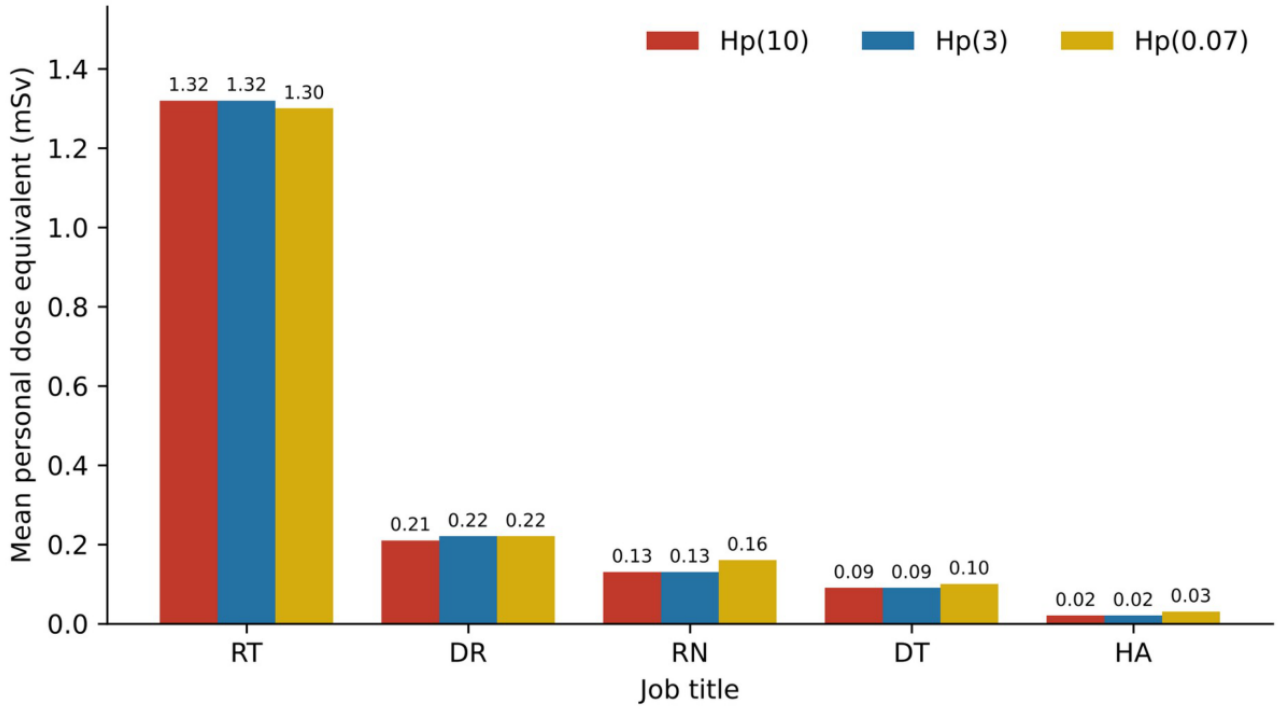


Figure 2: Mean personal dose equivalents Hp (10), Hp (3), and Hp (0.07) by job title in the radiology department (values as in Table 1). The technologist mean is inflated by one record of 46.12 mSv (Table S1). RT = Radiography technologists; DR = Medical doctors; RN = Registered nurses; DT = Darkroom technicians; HA = Health attendants.

equivalent (0.77 ± 1.96 mSv; 0.52 ± 0.72 mSv after excluding the two records flagged above 6 mSv, Table S1), whereas registered nurses maintained low exposure levels (0.19 ± 0.31 mSv). This finding does not align with several studies by Jabeen *et al.* [30], Masood *et al.* [32], and Samerdokiene *et al.* [33], which observed that occupational exposures in the radiotherapy department are relatively low since treatments are usually carried out using the external beam either from a linear accelerator or a highly protected Co-60 teletherapy sealed source. Brachytherapy treatments are also provided with a Cs-137 source, but using a remote after loading the machine. During irradiation, the staff remains outside the treatment room, reducing their occupational exposure.

The analysis unexpectedly found that health attendants in the radiotherapy department had the highest mean Hp (10), Hp (3), and Hp (0.07) (1.26 ± 0.97, 1.26 ± 0.97, and 1.28 ± 0.99 mSv, respectively; n = 5). In the year-stratified analysis (Table S2), job categories differed significantly only in 2021 (Hp (10): $H = 20.93$, $p < 0.001$); Dunn–Holm comparisons (Table S3) showed that health attendants (median 1.63 mSv) and medical doctors (0.22 mSv) had higher Hp (10) than registered nurses (0.02 mSv; adjusted $p = 0.011$ and $p < 0.001$, respectively), and medical doctors had higher Hp (10) than technologists (0.04 mSv; adjusted $p = 0.040$). No significant differences were found in 2022, 2023, or 2024. Given the small number of health attendant records, this finding should be interpreted cautiously, but it suggests possible gaps in radiation protection practices or badge handling for ancillary staff that warrant investigation.

3.5. Occupational doses in medical physics

In the medical physics department, only one job category (medical physicists) was represented. The mean personal dose equivalents Hp (10), Hp (3), and Hp (0.07) were 0.73 ± 0.85, 0.73 ± 0.85, and 0.74 ± 0.86 mSv, respectively, as represented in Table 1.

3.6. Comparison of interdepartmental whole-body Hp (10) occupational doses

Table 2 and Figure 5 present a comparison of Hp (10) annual median personal dose equivalents by job title across the three clinical departments: radiology, nuclear medicine, and radiotherapy/oncology; Figure 5 plots the same medians as Table 2. Apart from the health attendants in radiotherapy (see below), medical doctors/oncologists in the nuclear medicine department had the highest annual median personal dose equivalent of 0.72 (IQR 0.48) mSv, while radiopharmacists recorded 0.64 (IQR 0.36) mSv, compared with other healthcare workers. This finding aligns with the study by Phinsiri *et al.* [34], which reported that nuclear medicine staff are exposed to the highest average radiation dose, 0.038 mSv, compared to 0.023 mSv for those in diagnostic radiology. This highlights the increased radiation exposure associated with handling unsealed radiopharmaceutical sources. Unexpectedly, health attendants in the

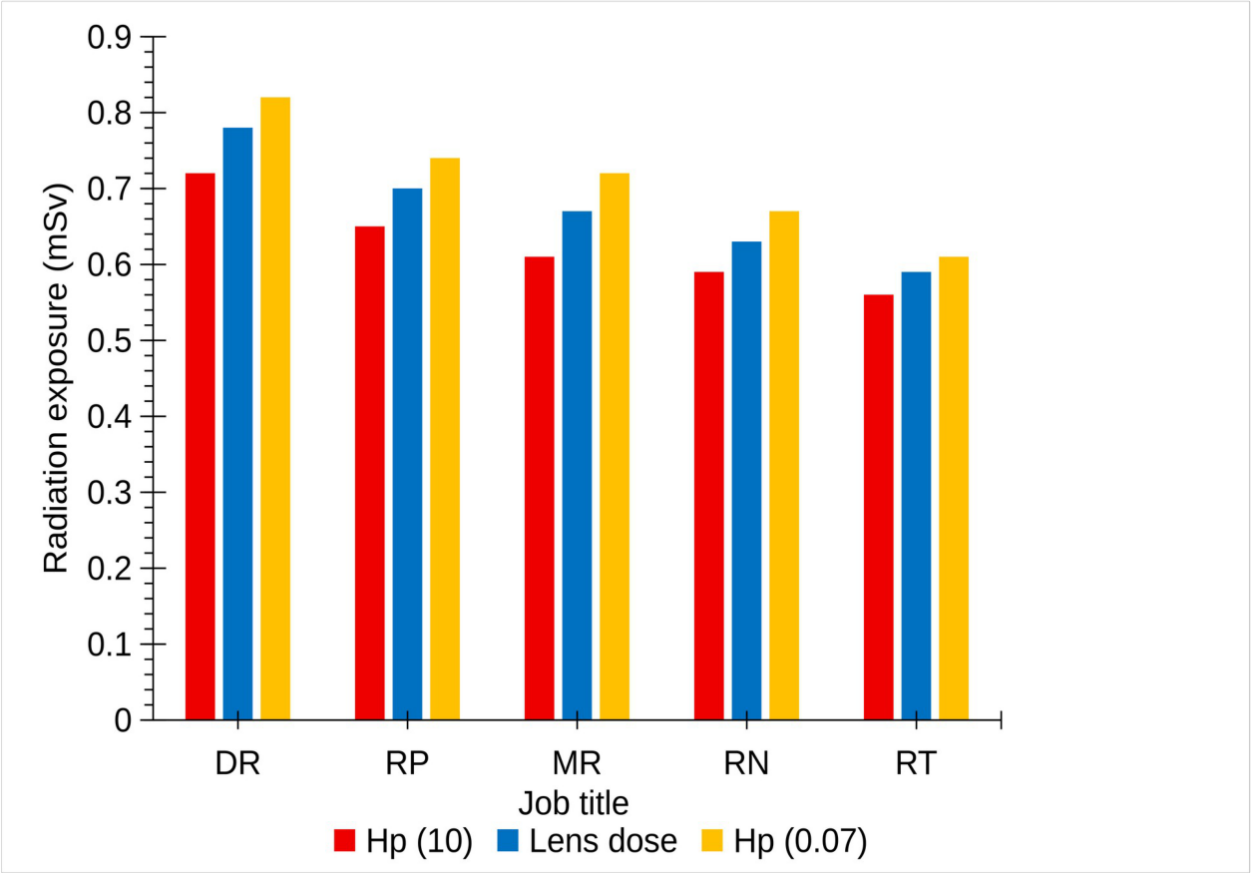


Figure 3: Occupational radiation dose levels by job title in the nuclear medicine department.

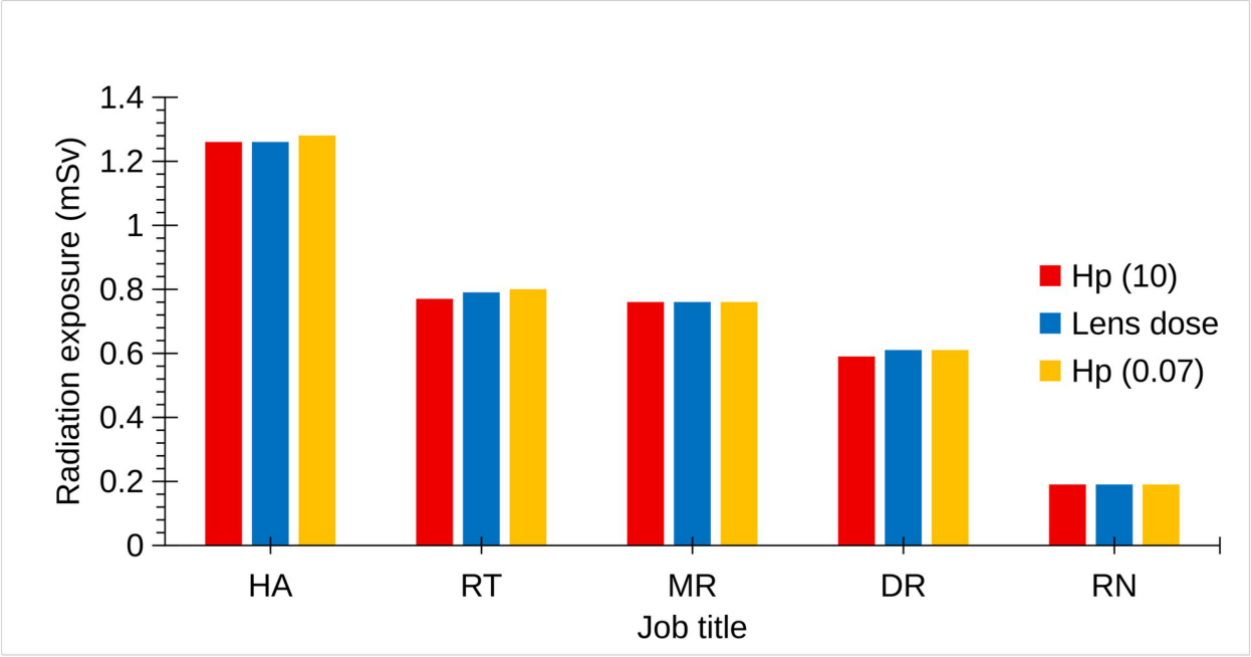


Figure 4: Occupational radiation dose levels by job title in the radiotherapy/oncology department.

radiotherapy/oncology department had the highest median, 1.01 (IQR 1.85) mSv, based on only five records; possible explanations are discussed in Section 3.8.

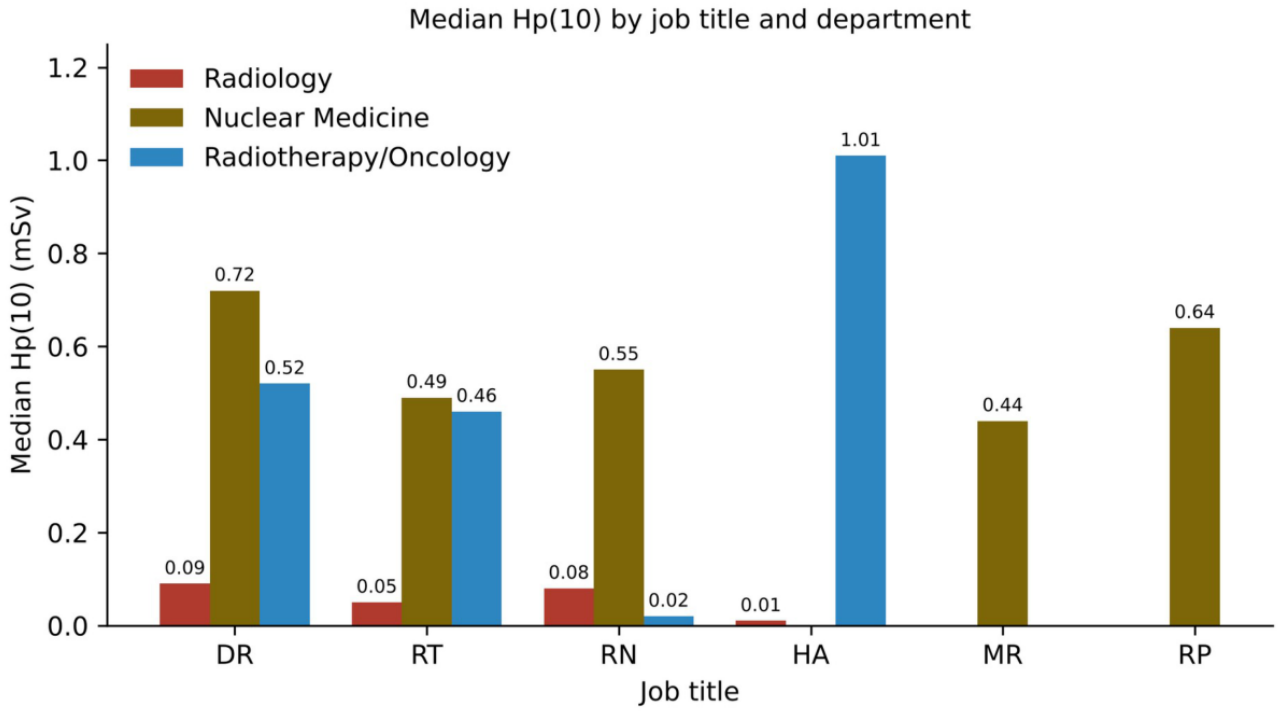


Figure 5: Comparison of median Hp (10) by job title in three departments: radiology, nuclear medicine, and radiotherapy/oncology (values as in Table 2).

3.7. Comparison of interdepartmental Hp (3) occupational doses (chest-level estimate of eye-lens dose)

Figure 6 and Table 2 compare the annual median Hp (3) personal dose equivalent across departments. The study revealed that medical doctors/oncologists and radiopharmacists in the nuclear medicine department had the highest Hp (3) values, 0.80 (IQR 0.64) and 0.64 (IQR 0.50) mSv, respectively, compared to other healthcare workers. Unexpectedly, health attendants in the radiotherapy/oncology department received the highest dose, 1.01 (IQR 1.85) mSv; this could be due to poor compliance with safety and monitoring guidelines. Hp (3) closely tracked Hp (10) for all groups. Because Hp (3) was estimated from the chest badge rather than measured at eye level, these values indicate the likely order of magnitude of lens exposure only, and dedicated eye-lens dosimetry is recommended for workers whose lens dose may exceed about 5 mSv per year [19, 21].

3.8. Comparison of interdepartmental Hp (0.07) skin doses (chest badge)

Figure 7 and Table 2 present a comparison of skin Hp (0.07) annual median personal dose equivalent, measured at the chest badge position, across departments. The study revealed that medical doctors/oncologists and radiopharmacists in the nuclear medicine department received the highest Hp (0.07) values of 0.83 (IQR 0.76) mSv and 0.63 (IQR 0.67) mSv, respectively, compared to other healthcare workers. As no ring or wrist dosimeters were used, these values do not represent hand or extremity doses, which can be substantially higher for staff who prepare and administer radiopharmaceuticals [12].

The health attendants in the radiotherapy and oncology department received the highest Hp (10), Hp (3), and Hp (0.07) values, possibly due to poor adherence to safety and monitoring guidelines. The analysis showed that the health attendants received unexpectedly high annual median personal dose equivalents: Hp (10) 1.01 (IQR 1.85) mSv; Hp (3) 1.01 (IQR 1.85) mSv; and Hp (0.07) 1.01 (IQR 1.89) mSv, respectively, even though their job role does not bring them directly into close contact with machine-emitting radiation, nor do they participate in the conduct of radiotherapy procedures. These values are based on only five records, two of which are identical in all three quantities (2.25, 2.25, and 2.29 mSv) and should be checked for duplicate entry. The likely explanation for this unusual finding may stem from inadequate adherence to safety and monitoring guidelines, including badges being stored or left in controlled areas when not worn; however, there is a need to research further to identify the factors responsible.

There is a need to strengthen institutional enforcement of personnel dosimetry monitoring. The highest individual value in this group (2.29 mSv) was well below the annual limits for effective dose (20 mSv), the lens of the eye (20 mSv), and the skin (500 mSv) [10].

Table 2: Median (IQR) personal dose equivalents by job category within departments, pooled over 2020–2024.

Departments	Job title	n	Hp (10)	Hp (3)	Hp (0.07)
			Median (IQR)	Median (IQR)	Median (IQR)
Diagnostic Radiology	Medical doctors	63	0.09 (0.26)	0.09 (0.29)	0.10 (0.28)
Diagnostic Radiology	Radiography technologists	38	0.05 (0.09)	0.05 (0.09)	0.06 (0.08)
Diagnostic Radiology	Registered nurses	4	0.08 (0.22)	0.08 (0.22)	0.11 (0.24)
Diagnostic Radiology	Health attendants	5	0.01 (0.03)	0.01 (0.03)	0.02 (0.03)
Diagnostic Radiology	Dark room technicians	3	0.12	0.12	0.10
Medical Physics	Medical Physicists	56	0.40 (0.76)	0.40 (0.76)	0.40 (0.77)
Nuclear Medicine	Medical doctors/Oncologists	12	0.72 (0.48)	0.80 (0.64)	0.83 (0.76)
Nuclear Medicine	Radiography technologists	11	0.49 (0.20)	0.49 (0.20)	0.49 (0.19)
Nuclear Medicine	Registered nurses	14	0.55 (0.26)	0.55 (0.39)	0.56 (0.52)
Nuclear Medicine	Radiopharmaceutical Pharmacists	6	0.64 (0.36)	0.64 (0.50)	0.63 (0.67)
Nuclear Medicine	Medical Records	5	0.44 (0.47)	0.44 (0.62)	0.45 (0.78)
Radiotherapy/ Oncology	Medical doctors/Oncologists	60	0.52 (0.75)	0.52 (0.75)	0.51 (0.75)
Radiotherapy/ Oncology	Radiography technologists	79	0.46 (0.63)	0.46 (0.63)	0.45 (0.63)
Radiotherapy/ Oncology	Registered nurses	24	0.02 (0.37)	0.02 (0.37)	0.02 (0.37)
Radiotherapy/ Oncology	Health Attendants	5	1.01 (1.85)	1.01 (1.85)	1.01 (1.89)

Values are presented as median (interquartile range); the IQR is not shown where $n < 4$. Pooled values are descriptive; year-stratified tests are given in Tables S2 and S3. Medical physics comprised a single job category, so no within-department test was possible.

3.9. Comparison of doses across departments

Pooled over 2020–2024, the inter-departmental comparison of median (IQR) Hp (10), Hp (3), and Hp (0.07) showed the highest values in nuclear medicine, Hp (10) 0.54 (IQR 0.40) mSv, followed by the radiotherapy department 0.47 (IQR 0.68) mSv and medical physics 0.40 (IQR 0.76) mSv, with the radiology department having the lowest dose 0.07 (IQR 0.20) mSv, as shown in Table 3. However, the departments were not monitored over the same years: all radiology records were from 2020–2021, all nuclear medicine records from 2024, medical physics records from 2022–2024, and radiotherapy records mainly from 2021–2024 (Table 3). The pooled differences are therefore confounded by monitoring year, including the COVID-19 period (Section 3.10).

When departments were compared within the same year (Table S2), no significant differences were found in 2021 (radiology vs radiotherapy, Hp (10) $p = 0.323$), 2022, or 2023 (medical physics vs radiotherapy), whereas in 2024 the departments differed (Hp (10): $H = 34.37$, $p < 0.001$); Dunn–Holm comparisons (Table S3) showed that medical physics staff (median 0.40 mSv) had lower Hp (10) than both nuclear medicine (0.54 mSv) and radiotherapy staff (0.56 mSv) (adjusted $p < 0.001$ for both), while nuclear medicine and radiotherapy did not differ (adjusted $p = 0.848$). These findings partly align with studies in Saudi Arabia by Nassef & Kinsara [31], Shubayr *et al.* [29], and in Thailand by Phinsiri *et al.* [34], where they found that the mean annual occupational radiation dose values for nuclear medicine staff were higher than those in radiology and radiotherapy, respectively; in the present data, nuclear medicine doses were higher than medical physics doses but did not differ from radiotherapy doses in the same year.

The researchers opined that this happens when workers in nuclear medicine use unsealed radioactive sources and during the preparation of radiopharmaceuticals. Apart from the single radiology record of 46.12 mSv discussed in Section 3.2, all annual Hp (10) and Hp (3) values were below 20 mSv, the ICRP annual limit for effective dose and for the equivalent dose to the lens of the eye (averaged over five years, with no single year above 50 mSv) [20, 35], and all Hp (0.07) values were below 50 mSv, i.e., far below the 500 mSv annual limit for the skin. Because records could not be linked to individual workers across years, compliance with the

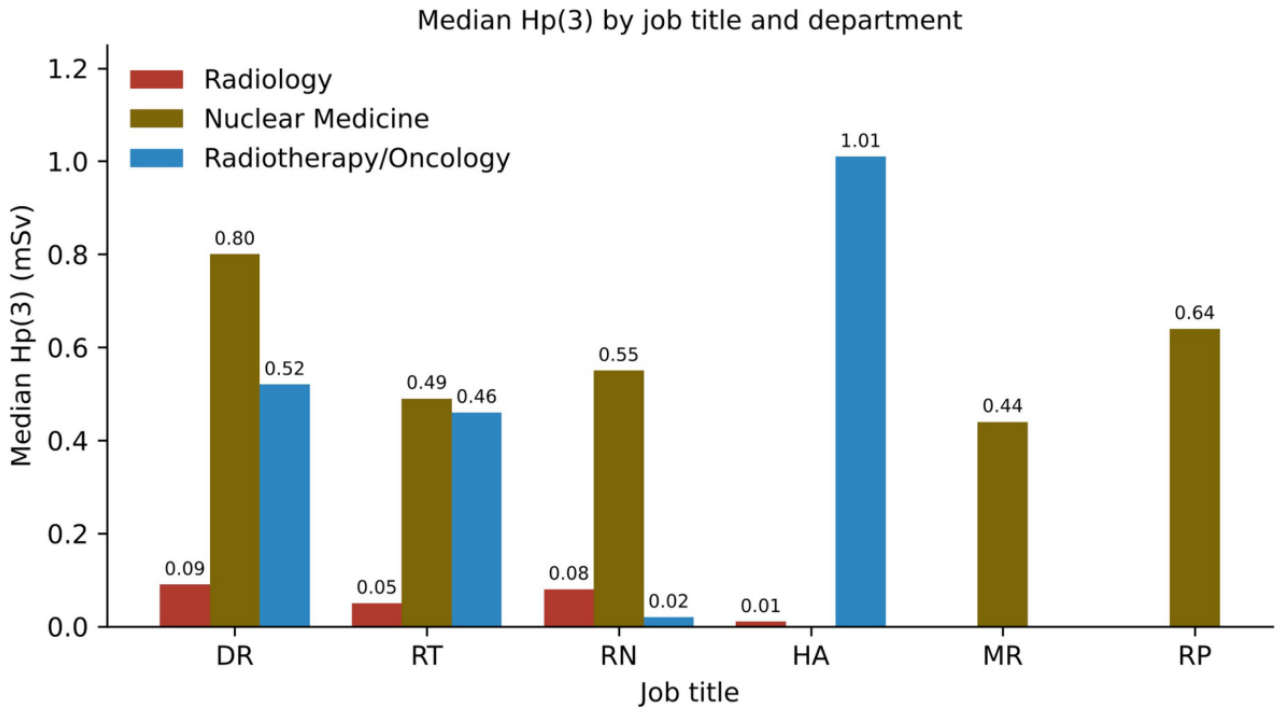


Figure 6: Comparison of median Hp (3) (chest-level estimate of eye-lens dose) by job title across departments (values as in Table 2).

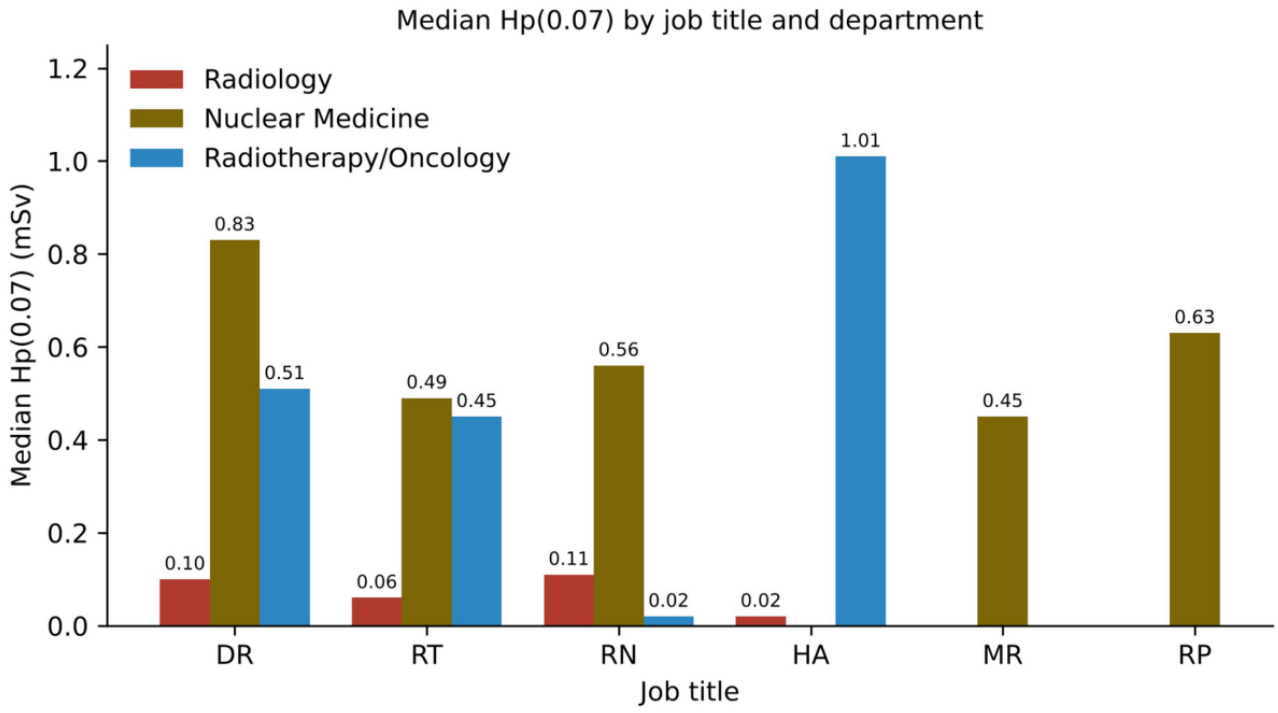


Figure 7: Comparison of median Hp (0.07) (skin dose at the chest badge position) by job title across departments (values as in Table 2).

five-year averaged limits (100 mSv in five years) could not be assessed for individual workers.

Table 3: Median (IQR) personal dose equivalents by department, pooled over 2020–2024 (descriptive).

	Radiotherapy/ Oncology	Nuclear Medicine	Medical Physics	Diagnostic Radiology
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
N	169	48	56	113
Hp (10)	0.47 (0.68)	0.54 (0.40)	0.40 (0.76)	0.07 (0.20)
Hp (3)	0.47 (0.69)	0.54 (0.55)	0.40 (0.76)	0.07 (0.20)
Hp (0.07)	0.46 (0.67)	0.54 (0.67)	0.40 (0.77)	0.07 (0.21)
Monitoring years	2020–2024	2024	2022–2024	2020–2021

IQR: interquartile range. Year-stratified tests are given in Table S2. One radiotherapy record lacked Hp (10), one radiotherapy record lacked Hp (3), and one radiology record lacked Hp (0.07).

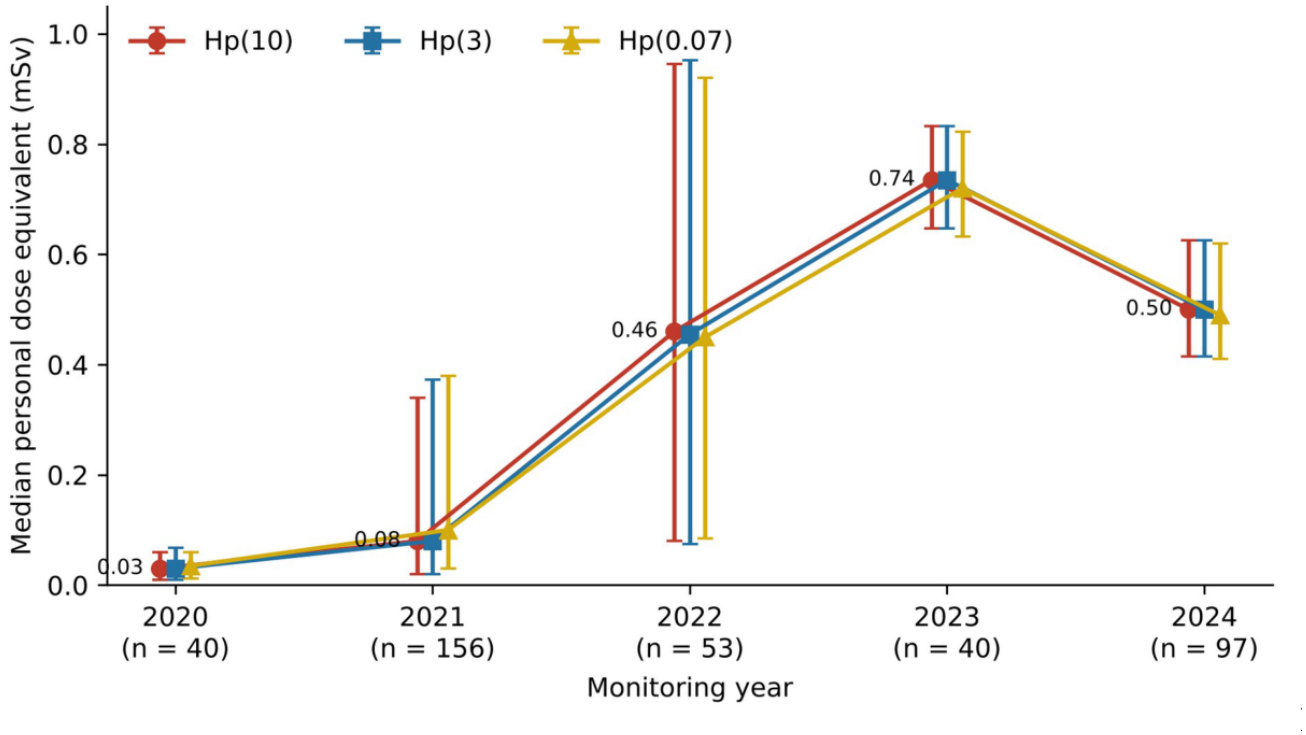


Figure 8: Annual median personal dose equivalents, 2020–2024 (error bars: interquartile range; n = records per year). The departments contributing records differ between years (Table 3).

3.10. Temporal trends in median occupational radiation dose

Figure 8 shows the observed trends in the annual median Hp (10), Hp (3), and Hp (0.07) during the study period. Annual median doses were lowest in 2020 (Hp (10) 0.03 mSv) and 2021 (0.08 mSv), rose to 0.46 mSv in 2022, peaked at 0.74 mSv in 2023, and declined slightly to 0.50 mSv in 2024; all annual medians were far below the annual dose limits. These overall trends must be interpreted with caution because the departments contributing records changed over time (radiology only in 2020–2021 and nuclear medicine only in 2024), so part of the apparent increase reflects the change in departmental mix rather than a change in exposure. Within radiotherapy/oncology, the only department monitored throughout 2021–2024, the median Hp (10) also increased from 0.05 mSv in 2021 to 0.46, 0.72, and 0.56 mSv in 2022, 2023, and 2024, respectively, which supports a genuine increase after the pandemic period in that department.

The lowest recorded doses between 2020 and 2021 coincided with the lockdown period during the COVID-19 pandemic, when strict movement restrictions were in place. This finding highlights the significant impact of the pandemic on hospitals' operations. The implications were that the COVID-19 lockdown resulted in a marked reduction in the conduct of non-emergency, elective diagnostic and interventional procedures, which account for the highest staff doses due to prolonged fluoroscopy screening time. There was also a decrease in nuclear medicine procedures, such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT) scans for cancer staging. This resulted in decreased exposure for technicians handling radiopharmaceuticals.

During the lockdown, radiological practices shifted from routine fluoroscopy to using portable X-rays and CT scans for managing COVID-19. It also led to changes in staffing and workflow. Hospitals restricted the number of personnel allowed in radiation zones and enforced the use of personal protective equipment (PPE), which may reduce exposure to scattered radiation. The lower doses may suggest delayed medical care due to a backlog of undiagnosed or untreated patients, potentially resulting in an increased number of procedures and higher occupational radiation doses post-lockdown in 2023. Our study's findings contradict those of a study that measured radiation dose to healthcare workers using thermoluminescent dosimetry, which indicates radiation exposure levels were comparable both before and during the COVID-19 pandemic [11].

4. Conclusion

This study focuses on the significance of long-term use of OSL dosimetry, which offers increased sensitivity, accuracy, and reproducibility compared to conventional methods for monitoring occupational radiation exposure among healthcare workers. It provides baseline data that can inform radiation protection policy and regulation in this setting. The findings support the feasibility of OSL dosimetry for routine occupational radiation monitoring in this setting. Overall, the findings revealed variations in annual personal dose equivalents across healthcare professional groups. Radiography technologists had the highest mean annual doses (0.92, 0.93, and 0.93 mSv for Hp (10), Hp (3), and Hp (0.07), respectively), but these means were driven by a single unverified record of 46.12 mSv, and their median doses were low, whereas darkroom technicians exhibited the lowest values.

Pooled over the study period, nuclear medicine had the highest median Hp (10), 0.54 (IQR 0.40) mSv, followed by the radiotherapy department 0.47 (IQR 0.68) mSv and medical physics 0.40 (IQR 0.76) mSv, with the radiology department having the lowest dose 0.07 (IQR 0.20) mSv, as shown in Table 3. Because the departments were monitored in different years, these pooled differences are confounded by monitoring year; within-year comparisons showed a significant inter-departmental difference only in 2024, when medical physics staff had lower doses than nuclear medicine and radiotherapy staff.

Apart from one record of 46.12 mSv, all annual Hp (10) and Hp (3) values were below 20 mSv, the ICRP annual limit for effective dose and for the equivalent dose to the lens of the eye (averaged over five years, with no single year above 50 mSv), and all Hp (0.07) values were far below the 500 mSv annual limit for the skin; the 46.12 mSv record did not exceed the 50 mSv single-year limit but requires verification. Because Hp (3) and Hp (0.07) were estimated from a chest-worn badge, they do not represent measured eye-lens or extremity doses. These results describe the observed dose levels only. Doses below the limits do not by themselves demonstrate that monitoring and compliance with safety regulations were effective; that would require separate evidence on badge-wearing compliance, dosimetry quality assurance, the application of investigation levels, staff training, and adherence to protective practices, particularly given the high variability among technologists and the unexpectedly high doses among ancillary staff.

Linking dose records to unique worker identifiers, formal investigation of records above investigation levels, and dedicated eye-lens and extremity dosimetry for high-exposure groups are recommended. The trend analysis showed fluctuations in annual median personal dose equivalent exposure. The lowest doses were recorded between 2020 and 2021, coinciding with the lockdown period and the COVID-19 pandemic, when strict movement restrictions were in place. Conversely, the highest doses were observed in 2023, followed by a slight decline in 2024, although part of this trend reflects changes in the departments monitored each year.

4.1. Recommendations for future studies

The following limitations were observed during this research. The use of a single chest-level OSLD badge to estimate the three personal dose equivalents of Hp (10), Hp (0.07), and Hp (3) reduces the accuracy of the occupational dose values. The use of two OSLD badges is suggested for future work; one specifically for Hp (3) eye lens dose and the other for Hp (10) and Hp (0.07).

There are suggestions of possible gaps in the radiation protection practices or badge handling for ancillary staff that require investigation.

Data availability

The data set for this research can be obtained upon request.

Declaration of competing interest

The authors have no conflict of interest.

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Ethical approval

Ethical approval was obtained from NHA (approval no.: NHA/EC/082/2025).

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Supplementary material

Table S1: Distributional summaries and verification of extreme records for radiography technologists (annual personal dose equivalents, mSv).

Group	Quantity	n	Mean ± SD	Median (IQR)	Range	P95	Mean ± SD excluding flagged records (n)
Radiography technologists, diagnostic radiology	Hp (10)	38	1.32 ± 7.47	0.06 (0.08)	0.00–46.12	3.37	0.11 ± 0.20 (37)
Radiography technologists, diagnostic radiology	Hp (3)	38	1.32 ± 7.47	0.06 (0.08)	0.00–46.12	3.37	0.11 ± 0.20 (37)
Radiography technologists, diagnostic radiology	Hp (0.07)	37	1.30 ± 7.19	0.06 (0.08)	0.00–43.82	5.44	0.12 ± 0.21 (36)
Radiography technologists, radiotherapy/oncology	Hp (10)	79	0.77 ± 1.96	0.46 (0.62)	0.00–16.19	3.64	0.52 ± 0.72 (77)
Radiography technologists, radiotherapy/oncology	Hp (3)	78	0.79 ± 2.01	0.46 (0.62)	0.00–16.19	3.65	0.52 ± 0.74 (76)
Radiography technologists, radiotherapy/oncology	Hp (0.07)	79	0.80 ± 2.04	0.45 (0.63)	0.00–16.19	3.64	0.52 ± 0.73 (77)
Radiography technologists, all departments	Hp (10)	128	0.92 ± 4.32	0.21 (0.53)	0.00–46.12	2.46	0.40 ± 0.61 (125)
Radiography technologists, all departments	Hp (3)	127	0.93 ± 4.35	0.21 (0.53)	0.00–46.12	2.61	0.40 ± 0.62 (124)
Radiography technologists, all departments	Hp (0.07)	127	0.93 ± 4.17	0.25 (0.53)	0.00–43.82	2.71	0.41 ± 0.62 (124)

Flagged records exceeded 6 mSv in at least one quantity: record 28 (diagnostic radiology, 2021: 46.12, 46.12, 43.82 mSv); record 308 (radiotherapy, 2022: 16.19, 16.19, 16.19 mSv); and record 374 (radiotherapy, 2024: 5.01, 5.99, 7.06 mSv), in Hp (10), Hp (3), and Hp (0.07), respectively. These were retained pending verification by the RSO. P95: 95th percentile. Medians and IQRs may differ from Table 2 by 0.01 mSv because of rounding.

Table S2: Year-stratified Kruskal–Wallis tests (each worker contributes at most one record per year).

Comparison	Year	Groups compared (n)	Hp (10) H; p	Hp (3) H; p	Hp (0.07) H; p
Job categories within radiology	2020	HA 3, DR 19, RT 16 (excluded: DT 1)	0.46; 0.796	0.74; 0.689	0.41; 0.816
Job categories within radiology	2021	DR 44, RT 22, RN 4 (excluded: DT 2, HA 2)	2.99; 0.224	3.16; 0.206	2.10; 0.350
Job categories within nuclear medicine	2024	DR 12, MR 5, RT 11, RP 6, RN 14	3.43; 0.488	3.23; 0.521	2.06; 0.725
Job categories within radiotherapy/oncology	2021	HA 4, DR 25, RT 32, RN 20	20.93; < 0.001	21.96; < 0.001	20.59; < 0.001
Job categories within radiotherapy/oncology	2022	DR 22, RT 21	0.16; 0.688	0.27; 0.605	0.17; 0.679
Job categories within radiotherapy/oncology	2023	DR 7, RT 14 (excluded: HA 1, MR 1, RN 2)	3.23; 0.072	3.23; 0.072	3.23; 0.072
Job categories within radiotherapy/oncology	2024	DR 4, RT 12 (excluded: RN 2)	0.63; 0.429	0.63; 0.429	0.53; 0.466
Between departments	2020	Radiology 39, Radiotherapy/oncology 1 – not testable (fewer than two groups with $n \geq 3$)	–	–	–
Between departments	2021	Radiology 74, Radiotherapy/oncology 81	0.98; 0.323	0.76; 0.385	3.80; 0.051
Between departments	2022	Medical physics 10, Radiotherapy/oncology 43	0.30; 0.585	0.31; 0.577	0.42; 0.517
Between departments	2023	Medical physics 15, Radiotherapy/oncology 25	0.85; 0.356	0.85; 0.356	0.55; 0.459
Between departments	2024	Medical physics 31, Nuclear medicine 48, Radiotherapy/oncology 18	34.37; < 0.001	34.46; < 0.001	33.80; < 0.001

H: Kruskal–Wallis statistic. Groups with fewer than three records were excluded. DR: medical doctors; RT: technologists; RN: nurses; HA: attendants; DT: darkroom technicians; MR: records; RP: pharmacists. No within-department test was possible for medical physics. Group counts refer to Hp (10) and may differ by one for other quantities.

Table S3: Dunn's post-hoc comparisons with Holm adjustment for strata with a significant Kruskal–Wallis test.

Stratum	Comparison	Hp (10) z; adjusted p	Hp (3) z; adjusted p	Hp (0.07) z; adjusted p
Job categories within radiotherapy/oncology, 2021	HA (1.63) vs DR (0.22)	0.88; 0.376	0.84; 0.400	0.67; 0.501
Job categories within radiotherapy/oncology, 2021	HA (1.63) vs RT (0.04)	2.19; 0.085	2.20; 0.083	1.97; 0.147
Job categories within radiotherapy/oncology, 2021	HA (1.63) vs RN (0.02)	3.07; 0.011	3.07; 0.011	2.88; 0.020
Job categories within radiotherapy/oncology, 2021	DR (0.22) vs RT (0.04)	2.57; 0.040	2.71; 0.027	2.59; 0.039
Job categories within radiotherapy/oncology, 2021	DR (0.22) vs RN (0.02)	4.01; < 0.001	4.13; < 0.001	4.08; < 0.001
Job categories within radiotherapy/oncology, 2021	RT (0.04) vs RN (0.02)	1.81; 0.139	1.80; 0.143	1.87; 0.147
Between departments, 2024	Medical physics (0.40) vs Nuclear medicine (0.54)	-5.47; < 0.001	-5.48; < 0.001	-5.41; < 0.001
Between departments, 2024	Medical physics (0.40) vs Radiotherapy/oncology (0.56)	-4.44; < 0.001	-4.44; < 0.001	-4.43; < 0.001
Between departments, 2024	Nuclear medicine (0.54) vs Radiotherapy/oncology (0.56)	-0.19; 0.848	-0.19; 0.850	-0.23; 0.815

Parenthetical values are median Hp (10) (mSv). z: Dunn z statistic (positive values indicate higher ranks in the first group); p-values were Holm adjusted within each stratum and quantity.