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Original Article

Assessment of Thyroid Hormone Levels and the Potential Risk of Hypothyroidism in Healthcare Workers Exposed to Low-Dose Ionizing Radiation

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ABSTRACT

Background: Healthcare professionals working in radiology and nuclear medicine may experience repeated occupational exposure to low-dose ionizing radiation, while the thyroid is a radiosensitive endocrine organ. Evidence concerning thyroid dysfunction among occupationally exposed healthcare workers remains limited in Pakistan. Objective: To assess thyroid hormone profiles and the association between occupational radiation exposure and hypothyroidism among radiology and nuclear medicine personnel. Methods: This cross-sectional study included 44 healthcare professionals from the Institute of Nuclear Medicine and Oncology, Lahore. Occupational information and exposure history were collected through a questionnaire, annual radiation exposure categories were obtained from personal dosimetry records, and serum thyroid-stimulating hormone (TSH), free thyroxine (FT4), and free triiodothyronine (FT3) were assessed. Results: Overall, 13/44 (29.5%) participants were classified as having hypothyroidism. Hypothyroidism occurred in 2/17 (11.8%) radiology personnel and 11/27 (40.7%) nuclear medicine personnel (exact p=0.0496). Prevalence increased across exposure-duration categories from 0% at 1–5 years to 52.6% at ≥16 years (exact p=0.0385). Hypothyroidism occurred in 3/27 (11.1%) participants within the normal radiation-exposure category and 10/17 (58.8%) in the higher-than-normal category (exact p=0.0016; crude prevalence ratio 5.29, 95% CI 1.70–16.53). TSH distributions differed significantly between exposure groups (p=0.0026), whereas FT4 and FT3 category distributions did not reach statistical significance. Conclusion: Higher recorded occupational radiation exposure and longer exposure duration were associated with a greater prevalence of hypothyroidism in this sample. The cross-sectional design does not establish causation, but the findings support continued occupational dosimetry, radiation-protection measures, and appropriate thyroid health surveillance. Keywords: occupational radiation exposure; thyroid dysfunction; TSH; FT3; FT4; ionizing radiation; hypothyroidism; radiology; nuclear medicine.

INTRODUCTION

Radiation is an established component of the physical environment and is broadly classified as ionizing and non-ionizing radiation. Ionizing radiation carries sufficient energy to remove electrons from atoms and molecules and is therefore capable of producing biological damage. Its medical applications are essential to modern diagnostic imaging, interventional procedures, nuclear medicine, and radiotherapy, but these applications can expose both patients and healthcare personnel to radiation. The biological

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consequences depend on radiation type, absorbed dose, dose rate, tissue radiosensitivity, age at exposure, and the duration and pattern of exposure (1).

Radiation-related health effects have traditionally been described as tissue reactions, historically termed deterministic effects, and stochastic effects. Tissue reactions generally occur above a threshold dose, with severity increasing as the dose rises, and may include radiation-induced skin injury, epilation, and cataract formation (1,2). Stochastic effects differ in that their probability, rather than severity, increases with dose; carcinogenesis and heritable effects have traditionally been considered within this category (2,3). Acute exposure involves delivery of a comparatively large radiation dose within a short period, whereas chronic occupational exposure may involve smaller repeated doses accumulated over prolonged periods, a distinction particularly relevant to medical personnel who work around radiation sources throughout their careers (1–3).

Because unnecessary radiation exposure should be minimized even when individual exposures remain within regulatory limits, radiation protection is centred on justification, optimisation, and dose limitation. The principle of keeping exposure as low as reasonably achievable is fundamental to occupational radiation protection (4). International Commission on Radiological Protection recommendations specify an occupational effective-dose limit of 20 mSv per year averaged over defined five-year periods while permitting a higher dose in an individual year within the Commission's stated limits (4). These limits do not remove the need for optimisation, personal dosimetry, shielding, appropriate distance from radiation sources, and reduction of unnecessary exposure time (4).

Healthcare workers represent an important occupational group because the use of radiological and nuclear techniques has expanded substantially. Studies have demonstrated deficiencies in radiation-hazard knowledge and variable implementation of protective practices among healthcare personnel, reinforcing the importance of training, dosimetry, and institutional safety systems (5,6). Occupational exposure patterns may vary across conventional radiography, computed tomography, fluoroscopy, nuclear medicine, and other radiation-based services because procedural workload, proximity to radiation sources, time spent in exposed areas, and use of protective measures differ between working environments (4–6).

The thyroid gland is located in the anterior neck and plays a central role in metabolism, growth, and development through the secretion of thyroxine and triiodothyronine. Thyroid-stimulating hormone released from the anterior pituitary regulates thyroid hormone synthesis under hypothalamic thyrotropin-releasing hormone control (7). Disruption of this hypothalamic-pituitary-thyroid axis can produce biochemical and clinical thyroid dysfunction. Hypothyroidism may be associated with fatigue, weight gain, cold intolerance, and, when clinically important, cardiovascular, metabolic, and neurocognitive consequences (7).

The thyroid is also recognised as a radiosensitive organ. Evidence from populations exposed to therapeutic radiation, nuclear accidents, and other higher-dose settings has established associations between radiation exposure and thyroid neoplasia and has also documented radiation-related functional thyroid impairment (8,9). Although such higher-dose evidence cannot be directly extrapolated to contemporary occupational low-dose exposure, it provides biological support for investigating thyroid outcomes in chronically exposed workers (8,9).

Potential mechanisms of radiation-associated thyroid injury include direct cellular and DNA damage as well as indirect effects mediated through oxidative stress, microvascular injury, inflammatory responses, and altered immune regulation (8,10). Ionizing radiation can generate reactive oxygen species capable of lipid peroxidation, protein modification, and DNA injury (8,10). With repeated exposure, cumulative biological stress may potentially influence thyroid structure or function even when each individual exposure is relatively small, although the magnitude and clinical importance of such effects at contemporary occupational doses remain uncertain (8–10).

Iodine nutrition is another potentially important determinant of thyroid susceptibility. Iodine deficiency increases thyroid stimulation through the hypothalamic-pituitary-thyroid axis and changes thyroid physiology and follicular-cell activity (11). Consequently, iodine status may modify thyroid function independently of radiation exposure and may potentially influence interpretation of occupational thyroid studies. This issue is particularly relevant in populations where iodine sufficiency is not uniform (11).

Several occupational studies have examined thyroid function among workers exposed to low-dose ionizing radiation. Wong et al. followed hospital workers occupationally exposed to radiation and reported progressive reductions in serum T3 and T4 associated with exposure duration, with an increase in TSH appearing later during follow-up (12). A meta-analysis of radiation workers also reported

alterations in thyroid hormone profiles in occupationally exposed populations (13). Other investigations have described associations between occupational radiation exposure, exposure duration, or cumulative dose and thyroid-hormone abnormalities (14,15).

Cioffi et al. compared exposed healthcare workers with unexposed healthcare personnel and found higher average TSH and lower FT3 and FT4 among exposed workers, with hypothyroidism identified more frequently in the exposed group (16). Tu et al. similarly reported thyroid-function alterations in medical occupational populations exposed to low-dose ionizing radiation, with exposure duration emerging as an important occupational characteristic (17). Collectively, these observations are relevant to healthcare settings because occupational exposure may continue for many years even when individual annual exposures are comparatively low (12,14–17).

Longer-term occupational studies provide additional context. A Canadian cohort of medical radiation workers investigated health outcomes associated with low-dose ionizing-radiation exposure over extended follow-up (18). Structural thyroid outcomes have also been studied, although findings have not always been uniform; for example, an occupational study of healthcare personnel did not demonstrate an association between radiation exposure and thyroid nodules (19). More recently, a retrospective cohort of healthcare workers reported a greater incidence of thyroid alterations among radiation-exposed personnel over long-term follow-up (20). Such variation indicates that radiation-associated thyroid findings may depend on the exposure metric, thyroid endpoint examined, characteristics of the underlying population, and control of potential confounding factors (12–20).

Evidence from therapeutic irradiation further demonstrates that thyroid tissue can undergo structural and functional changes after substantially higher radiation doses. Longitudinal studies after head-and-neck radiotherapy have documented changes in thyroid volume and function (21). Hypothyroidism has also been reported after radiotherapy for Hodgkin lymphoma and other malignancies, with thyroid dose-volume relationships influencing subsequent dysfunction (22,23). Long-term radiation effects include benign and malignant thyroid outcomes, although the dose ranges in therapeutic studies are substantially greater than those normally encountered occupationally (24,25). Earlier clinical follow-up after cytotoxic and radiation-based treatment also demonstrated delayed endocrine dysfunction, reinforcing the importance of considering latency when evaluating radiation-associated thyroid effects (26).

Radiology and nuclear medicine personnel therefore constitute an important population for occupational-health surveillance. Their occupational exposures are generally substantially lower than therapeutic radiation doses but may recur over many years (4,12–20). The potential interaction between exposure intensity, duration of employment, occupational setting, individual susceptibility, and other determinants of thyroid function makes direct evaluation within healthcare workforces important (11,12,14–20).

At institutions such as the Institute of Nuclear Medicine and Oncology, Lahore, locally generated evidence may help define the pattern of thyroid-function abnormalities among radiation-exposed personnel. Most occupational evidence represented in the literature assembled for the present study derives from healthcare-worker populations outside Pakistan, with substantial variation in exposure assessment, duration of follow-up, and thyroid outcomes evaluated (12–20). This provides a rationale for examining the association within a local occupational setting. The present study therefore aimed to assess serum thyroid hormone profiles among radiology and nuclear medicine healthcare workers at INMOL and to examine the association of recorded occupational radiation exposure, exposure duration, and occupational department with hypothyroidism.

MATERIALS AND METHODS

A cross-sectional analytical study was conducted among healthcare professionals working in the radiology and nuclear medicine services of the Institute of Nuclear Medicine and Oncology, Lahore. The setting includes clinical services in which healthcare workers may be occupationally exposed to ionizing radiation during routine radiological and nuclear medicine activities.

The estimated accessible population consisted of 50 workers. The target sample was 44 participants. This sample size was consistent with the Krejcie and Morgan sample-size table for a finite population of 50 (27). The finite-population expression (n=N/(1+Ne^2)), where (N=50) and the precision level (e=0.05),

also yields approximately 44 participants. Participants were selected using simple random sampling from the eligible population.

Workers from radiology and nuclear medicine with at least one year of occupational exposure to ionizing radiation were eligible. Personnel working outside the radiology and nuclear medicine services were excluded. The study was conducted over approximately four months after ethical approval by the Ethical Review Board of The Superior University, Lahore. Participant anonymity and confidentiality were maintained, participation was voluntary, and participants were permitted to withdraw without penalty.

A structured questionnaire was used to collect demographic characteristics, occupational information, and history of radiation exposure. Recorded variables included sex, age group, occupational department, and duration of occupational radiation exposure. Age was classified as 20–30 or 31–40 years. Exposure duration was categorized as 1–5, 6–10, 11–15, and ≥16 years.

Occupational radiation-exposure information was obtained from personal dosimetry records maintained by the hospital radiation-safety department. For analysis, the recorded annual exposure information was categorized into two groups: within the normal annual range and higher than the normal annual range. Departmental exposure was additionally represented by employment in radiology or nuclear medicine.

Thyroid function was evaluated using serum TSH, FT4, and FT3. Each thyroid-function parameter was categorized as normal, high, or low according to the laboratory classification available for the study. Thyroid-function tests are interpreted jointly because TSH and circulating free thyroid hormones provide complementary information regarding thyroid functional status (28). Hypothyroidism was analysed as a binary study outcome according to the thyroid-function classification recorded for each participant.

The original data were entered and analysed using IBM SPSS Statistics version 27 and Microsoft Excel 2021. Frequencies and percentages were calculated for demographic characteristics, occupational exposure variables, and thyroid-function categories. Cross-tabulations were used to examine relationships between occupational department, duration of radiation exposure, recorded radiation-exposure category, and thyroid outcomes. Because the total sample was small and several contingency tables contained sparse expected cell counts, exact tests were used for corrected inferential reporting. Fisher's exact test was applied to 2×2 comparisons, and the Fisher–Freeman–Halton extension was used for sparse larger contingency tables. Exact probabilities were recalculated using Python 3.13.5 with SciPy 1.17.0. For the principal comparison between radiation-exposure category and hypothyroidism, a crude prevalence ratio with a 95% confidence interval was calculated as an exploratory effect estimate using statsmodels 0.14.6. Statistical significance was defined as $p<0.05$.

RESULTS

A total of 44 healthcare professionals completed the questionnaire and underwent thyroid-function assessment. The overall demographic and occupational profile is presented comprehensively in Table 1. Most participants were male, more than half were aged 20–30 years, and nearly two-thirds worked in nuclear medicine. A substantial proportion had prolonged occupational exposure: 19/44 (43.2%) had worked with radiation for ≥16 years. Personal dosimetry records classified 27/44 (61.4%) participants within the normal annual radiation-exposure category and 17/44 (38.6%) within the higher-than-normal category. Overall, 13/44 (29.5%) participants were classified as having hypothyroidism.

Table 1. Demographic, Occupational, Radiation-Exposure, and Thyroid-Outcome Characteristics of the Study Participants

Characteristic	Category	n	%
Total sample	All participants	44	100.0
Sex	Male	37	84.1
	Female	7	15.9
Age group	20–30 years	24	54.5
	31–40 years	20	45.5
Occupational department	Radiology	17	38.6
	Nuclear medicine	27	61.4
Duration of occupational radiation exposure	1–5 years	6	13.6
	6–10 years	8	18.2
	11–15 years	11	25.0
	≥16 years	19	43.2
Recorded annual radiation-exposure category	Normal annual range	27	61.4
	Higher-than-normal range	17	38.6
Hypothyroidism status	Yes	13	29.5
	No	31	70.5

Hypothyroidism differed according to both occupational department and duration of radiation exposure (Table 2). Among radiology personnel, 2/17 (11.8%) had hypothyroidism compared with 11/27 (40.7%) nuclear medicine personnel. The departmental difference was statistically significant using Fisher's exact test (p=0.0496).

A progressively greater prevalence of hypothyroidism was also observed across increasing categories of occupational exposure duration. No participant with 1–5 years of exposure was classified as hypothyroid. Hypothyroidism was identified in 1/8 (12.5%) participants with 6–10 years of exposure, 2/11 (18.2%) with 11–15 years, and 10/19 (52.6%) with ≥16 years. The overall association between duration category and hypothyroidism was statistically significant on exact testing (p=0.0385).

Table 2. Comprehensive Association of Occupational Department and Exposure Duration With Hypothyroidism

Occupational Variable	Category	Total n	Hypothyroidism Yes n (%)	Hypothyroidism No n (%)	Exact p Value
Department	Radiology	17	2 (11.8)	15 (88.2)	0.0496
	Nuclear medicine	27	11 (40.7)	16 (59.3)	
Exposure duration	1–5 years	6	0 (0.0)	6 (100.0)	0.0385
	6–10 years	8	1 (12.5)	7 (87.5)	
	11–15 years	11	2 (18.2)	9 (81.8)	
	≥16 years	19	10 (52.6)	9 (47.4)	

A marked difference in hypothyroidism prevalence was observed between the two recorded radiation-exposure categories (Table 3). Among participants within the normal annual exposure range, 3/27 (11.1%) had hypothyroidism and 24/27 (88.9%) did not. In the higher-than-normal exposure category, 10/17 (58.8%) had hypothyroidism and 7/17 (41.2%) did not.

The association was statistically significant by Fisher's exact test (p=0.0016). The crude prevalence of hypothyroidism in the higher-exposure category was approximately 5.29 times the prevalence observed in the normal-exposure category (PR 5.29, 95% CI 1.70–16.53). This is an unadjusted estimate and does not account for possible differences in age, sex, duration of employment, iodine status, or other thyroid-related factors.

Table 3. Association Between Recorded Annual Radiation-Exposure Category and Hypothyroidism

Radiation-Exposure Category	Total n	Hypothyroidism Yes n (%)	Hypothyroidism No n (%)	Crude Prevalence Ratio	95% CI	Exact p Value
Normal annual range	27	3 (11.1)	24 (88.9)	1.00	Reference	
Higher-than-normal range	17	10 (58.8)	7 (41.2)	5.29	1.70–16.53	0.0016
Total	44	13 (29.5)	31 (70.5)			

The complete distribution of TSH, FT4, FT3, and hypothyroidism according to radiation-exposure category is shown in Table 4. This integrated table permits direct comparison of all measured thyroid outcomes without requiring separate graphical presentation.

Table 4. Comprehensive Distribution of Thyroid-Function Parameters and Hypothyroidism According to Radiation-Exposure Category

Thyroid Variable	Category	Normal Exposure n (%) n=27	Higher Exposure n (%) n=17	Total n (%) n=44	Exact p Value	Statistical Interpretation
TSH	Normal	24 (88.9)	7 (41.2)	31 (70.5)	0.0026	Significant
	High	3 (11.1)	8 (47.1)	11 (25.0)		
	Low	0 (0.0)	2 (11.8)	2 (4.5)		
FT4	Normal	24 (88.9)	11 (64.7)	35 (79.5)	0.0627	Not significant
	High	0 (0.0)	2 (11.8)	2 (4.5)		
	Low	3 (11.1)	4 (23.5)	7 (15.9)		
FT3	Normal	24 (88.9)	10 (58.8)	34 (77.3)	0.0683	Not significant
	High	2 (7.4)	4 (23.5)	6 (13.6)		
	Low	1 (3.7)	3 (17.6)	4 (9.1)		
Hypothyroidism	Yes	3 (11.1)	10 (58.8)	13 (29.5)	0.0016	Significant
	No	24 (88.9)	7 (41.2)	31 (70.5)		

Abbreviations: TSH, thyroid-stimulating hormone; FT4, free thyroxine; FT3, free triiodothyronine; CI, confidence interval. Percentages in exposure-group columns are calculated using the corresponding group denominator. Exact probabilities were used because of the small sample and sparse contingency-table cells.

For TSH, 24/27 participants (88.9%) in the normal-exposure group had values within the normal category, three (11.1%) had high TSH, and none had low TSH. In the higher-exposure group, only 7/17 (41.2%) had normal TSH, whereas 8/17 (47.1%) had high TSH and 2/17 (11.8%) had low TSH. The overall TSH distribution differed significantly between radiation-exposure categories (exact p=0.0026).

For FT4, 24/27 participants (88.9%) in the normal-exposure category had normal values, 3/27 (11.1%) had low values, and none had high FT4. Among participants in the higher-exposure category, 11/17 (64.7%) had normal FT4, 2/17 (11.8%) had high FT4, and 4/17 (23.5%) had low FT4. Although FT4 abnormalities were numerically more frequent in the higher-exposure category, the overall difference did not reach statistical significance on exact testing (p=0.0627).
For FT3, 24/27 participants (88.9%) in the normal-exposure category had normal values, 2/27 (7.4%) had high FT3, and 1/27 (3.7%) had low FT3. In the higher-exposure category, 10/17 (58.8%) had normal FT3, 4/17 (23.5%) had high values, and 3/17 (17.6%) had low values. The overall FT3 distribution did not reach statistical significance on exact testing (p=0.0683).
The integrated comparison therefore demonstrated statistically significant differences for hypothyroidism status and TSH distribution, whereas the FT4 and FT3 distributions showed numerical differences without meeting the conventional threshold for statistical significance.

DISCUSSION

The present study identified an association between occupational radiation-exposure characteristics and thyroid dysfunction among radiology and nuclear medicine healthcare workers at INMOL. Approximately three in ten participants were classified as having hypothyroidism. The prevalence was substantially greater among workers in the higher-than-normal radiation-exposure category than among those in the normal-exposure category, and the crude prevalence ratio indicated an approximately fivefold difference. Hypothyroidism was also progressively more frequent across increasing categories of exposure duration and was most common among personnel with ≥16 years of occupational exposure. Departmental differences were observed, with a higher prevalence among nuclear medicine than radiology personnel. Importantly, these findings represent unadjusted cross-sectional associations and cannot establish that occupational radiation exposure caused the observed thyroid abnormalities.
The principal finding is broadly consistent with occupational studies reporting altered thyroid function among healthcare workers exposed to low-dose ionizing radiation. Wong et al., in a longitudinal occupational cohort, reported declines in T3 and T4 with increasing exposure duration and a later increase in TSH during follow-up, supporting the possibility that prolonged low-dose exposure may be associated with measurable changes in thyroid physiology (12). Luna-Sánchez et al. also observed an association between dosimetric exposure and increased TSH in healthcare workers, including evidence consistent with subclinical hypothyroidism (15). Cioffi et al. found higher TSH and lower FT3 and FT4 among exposed healthcare workers than among non-exposed personnel and reported hypothyroidism more frequently among exposed workers (16). A more recent retrospective cohort similarly reported a greater occurrence of thyroid alterations among healthcare professionals exposed to low-dose ionizing radiation during extended follow-up (20).
The present results should nevertheless not be interpreted as demonstrating a uniform biochemical response to radiation exposure. Although the distribution of TSH categories differed significantly between the two exposure groups, the corresponding FT4 and FT3 category differences did not meet the conventional 0.05 threshold after exact testing. This distinction is important because the descriptive pattern showed more FT4 and FT3 abnormalities in the higher-exposure category, but the small sample produced substantial statistical uncertainty. Occupational studies have likewise not demonstrated completely consistent hormonal patterns. Sernia et al. reported changes in FT3 and FT4 among exposed healthcare workers without a corresponding occupationally related change in TSH, demonstrating that the direction and combination of thyroid-hormone changes may vary across populations (29). Differences in exposure magnitude and duration, laboratory methodology, age, sex, baseline thyroid status, iodine status, and other confounding factors may contribute to heterogeneity between occupational studies (11,12,14–17,20,29).
The association with exposure duration is biologically plausible but also requires careful interpretation. Hypothyroidism increased from 0% among workers with 1–5 years of exposure to 52.6% among those with ≥16 years. Previous occupational studies have also reported relationships between employment duration, cumulative exposure, and thyroid-hormone abnormalities (12–17). However, duration of employment is not equivalent to absorbed thyroid dose and should not be interpreted as a direct dosimetric measure (4,12,14–17). Workers with longer service are also generally older, while age and other individual characteristics may influence thyroid function and may be associated with duration of employment (15,20). Because the present analysis did not simultaneously adjust for age, sex, and

exposure duration, the independent contribution of occupational radiation dose cannot be separated from these correlated factors.

Evidence from therapeutic and higher-dose radiation exposure provides biological support for thyroid radiosensitivity, although these exposure conditions differ substantially from contemporary occupational exposure. Radiation-associated hypothyroidism has been described after external-beam radiotherapy, and dose-volume relationships have been reported in head-and-neck and lymphoma populations (9,21–23). Long-term follow-up has also established radiation-related structural thyroid changes and neoplastic outcomes (24–26). These findings demonstrate that thyroid tissue can be damaged by ionizing radiation but should not be used to assume that the same magnitude of effect occurs at the considerably lower doses encountered in routine occupational practice (8,9,21–26).

The current study's departmental finding also deserves cautious interpretation. Hypothyroidism occurred in 40.7% of nuclear medicine personnel compared with 11.8% of radiology personnel. Different radiation-related working environments can produce different exposure profiles because source type, procedural workload, proximity to radiation sources, exposure time, and use of protective measures vary across occupational activities (4–6). Nevertheless, department alone cannot identify the mechanism responsible for the observed difference. Individual dose, task distribution, workload, shielding, distance from the source, and time spent in radiation areas were not analysed separately in the present study. Consequently, the higher prevalence among nuclear medicine staff should be interpreted as a departmental association rather than evidence of inadequate radiation-protection practice.

The radiation-exposure classification demonstrated the clearest relationship with hypothyroidism. Only 11.1% of participants within the normal annual exposure category were classified as hypothyroid compared with 58.8% in the higher-than-normal exposure category. The crude prevalence ratio of 5.29 indicates a substantial unadjusted association, but its wide confidence interval reflects the small sample. Cioffi et al. similarly reported an association between occupational low-dose exposure and hypothyroidism, while Wong et al. demonstrated longitudinal hormone changes related to exposure duration (12,16). At the same time, not every occupational study has demonstrated thyroid structural disease associated with radiation exposure, emphasizing that functional and structural thyroid outcomes should not be treated as interchangeable endpoints (19).

Potential biological mechanisms include direct radiation-related cellular injury, DNA damage, oxidative stress, and subsequent alterations in thyroid tissue or regulatory pathways (8–10). Ionizing radiation can generate reactive oxygen species and induce molecular and cellular injury through pathways relevant to radiation-associated tissue effects (8,10). Repeated exposure could theoretically result in cumulative biological effects even when individual exposures are small; however, these mechanisms were not measured in the present study and therefore provide biological context rather than direct mechanistic evidence for the observed associations (8–10).

Iodine status represents another important potential confounder. Iodine availability influences thyroid hormone production, TSH stimulation, and thyroid morphology (11). The present study did not adjust for dietary iodine intake, and family history of thyroid disease and other occupational exposures were also not controlled. These factors could alter the prevalence of biochemical thyroid abnormalities independently of radiation exposure. More broadly, occupational studies of thyroid function have differed in the extent to which age, sex, baseline thyroid characteristics, exposure duration, and other potential confounders have been considered, which may contribute to variation between reported findings (12,14–17,20,29). Pre-existing thyroid disease, medication use, and other clinical factors may likewise be relevant when interpreting TSH, FT4, and FT3 values.

The predominantly male sample also limits assessment of sex-related differences. Thirty-seven of the 44 participants were male, leaving only seven female participants. Previous occupational research has identified sex and age as potentially relevant determinants of thyroid outcomes, including in long-term healthcare-worker cohorts (15,20). The current sample was therefore insufficient for reliable sex-stratified analysis, and no conclusion regarding differential radiosensitivity between male and female workers should be drawn from these data.

From an occupational-health perspective, the findings reinforce the importance of established radiation-protection principles. Personal dosimetry, shielding, appropriate distance, minimization of unnecessary exposure time, procedural training, and adherence to institutional and regulatory dose-control systems remain fundamental components of occupational radiation protection (4–6). Monitoring exposure is particularly important where radiation-related work continues over many years, while

longitudinal occupational studies demonstrate the value of considering cumulative exposure history rather than relying solely on a single cross-sectional assessment (12,15,18,20).

Given reports of thyroid-function alterations among occupationally exposed healthcare workers, periodic thyroid-health assessment may reasonably be considered within broader occupational surveillance programs, particularly for personnel with sustained exposure histories or comparatively greater recorded exposure (12,15,16,20). Such monitoring should complement rather than replace radiation-dose control and established radiation-protection practices (4–6). The present study does not determine an optimal screening interval or demonstrate that thyroid testing prevents radiation-related disease; rather, it supports consideration of thyroid surveillance as one component of occupational health monitoring in conjunction with dosimetry and exposure minimization.

The study contributes locally generated evidence from a Pakistani nuclear medicine and radiology workforce. Within the occupational literature represented in the present manuscript, most published studies derive from healthcare-worker populations outside Pakistan and use heterogeneous exposure metrics and thyroid endpoints (12–20,29). The use of personal-dosimetry records in the present study strengthens exposure classification compared with reliance solely on recalled occupational exposure and is consistent with the central role of dosimetric monitoring in radiation protection (4,12,15,20). The comprehensive tabular presentation also allows the observed distributions, denominators, effect estimate, and inferential results to be evaluated directly. At the same time, the small single-centre sample, categorical rather than continuous dose analysis, and absence of multivariable adjustment mean that the magnitude of the association should not be generalized without additional studies.

Future research would benefit from larger multicentre prospective cohorts with individual cumulative dosimetry, repeated thyroid-function testing, explicit laboratory reference ranges, and systematic measurement of potential confounders. Age, sex, baseline thyroid disease, thyroid medication, iodine intake, smoking, body mass index, occupational task, shielding practices, and cumulative dose should be incorporated where feasible. Existing longitudinal and occupational studies demonstrate the value of repeated exposure and thyroid assessment over time and illustrate the importance of considering individual and occupational covariates when examining low-dose radiation effects (12,14–17,20,29). Longitudinal designs would therefore clarify the temporal relationship between occupational exposure and changes in thyroid function more reliably than a single cross-sectional assessment.

CONCLUSION

Among the 44 radiology and nuclear medicine healthcare workers evaluated, hypothyroidism was more prevalent in the higher-than-normal occupational radiation-exposure category and among personnel with longer exposure duration. TSH category distributions also differed significantly between radiation-exposure groups, whereas FT4 and FT3 category distributions showed numerical differences that were not statistically significant on exact testing. Nuclear medicine personnel had a higher observed prevalence of hypothyroidism than radiology personnel.

These findings demonstrate an association between occupational radiation-exposure characteristics and thyroid dysfunction within the studied workforce but do not establish a causal relationship. Continued personal dosimetry, adherence to radiation-protection principles, and appropriate occupational thyroid-health surveillance are warranted, while larger longitudinal studies with individual cumulative dose measurements and adjustment for thyroid-related confounders are needed to define the relationship more precisely.

LIMITATIONS

The study involved a relatively small sample of 44 participants from a single institution, limiting precision and external generalizability. Its cross-sectional design measures exposure and thyroid status within the same study period and therefore cannot determine temporal sequence or establish causality.

Although personal dosimetry records were used for radiation-exposure classification, the analysis relied on categorical exposure groups rather than continuous cumulative thyroid or whole-body dose measurements. Duration of employment may correlate with both cumulative exposure and age, and the analysis did not adjust simultaneously for these factors. The small number of women also prevented meaningful sex-stratified analysis.

Some occupational information was obtained through questionnaire or clinical records and may therefore be subject to incomplete documentation or recall. Dietary iodine intake, family history of thyroid disease, and other occupational exposures were not adjusted for. The study also did not provide

multivariable estimates accounting for these potential confounders. These limitations should be considered when interpreting the magnitude of the reported associations.

RECOMMENDATIONS

Radiation-safety standards should continue to be rigorously implemented in healthcare facilities using ionizing radiation or radioactive materials. Personal dosimetry should be maintained consistently, and exposure records should be reviewed longitudinally to identify personnel with comparatively greater cumulative occupational exposure.

Occupational-health programs may incorporate periodic thyroid-function assessment, particularly for personnel with long radiation-work histories or higher recorded exposure. Training should reinforce appropriate shielding, distance from the radiation source, minimization of unnecessary exposure time, and correct use of personal protective equipment. Administrative measures such as appropriate task allocation or rotation may be considered where they can reduce avoidable cumulative exposure without compromising clinical services.

Centralized longitudinal occupational-health records linking dosimetry with relevant medical surveillance could facilitate earlier identification of health abnormalities, improve institutional radiation-safety evaluation, and support future evidence-based occupational-health policies.

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