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Research article

Blood oxidative stress parameters in hospital workers occupationally exposed to low doses of ionizing radiation: A systematic review and meta-analysis

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ABSTRACT

This study conducted a systematic review and meta-analysis to explore the relationship between blood oxidative stress biomarkers and exposure to low-dose ionizing radiation in medical radiation workers. The researchers searched PubMed, Scopus, Web of Science, and Google Scholar for relevant studies until February 2023. They assessed the quality of the studies using the Newcastle–Ottawa Scale (NOS) and used a random-effects model to combine the results. The I-square test was employed to assess study heterogeneity. The effect sizes were represented by standardized mean differences (proxied by Hedges' g) with a 95 % confidence interval. Out of 295 initial articles, 38 studies met the inclusion criteria for the meta-analysis. The systematic review results revealed a significant difference in blood oxidative stress biomarkers with exposure to low-dose ionizing radiation in medical radiation workers. Furthermore, the overall effect size of MDA was notably higher than that of the control group ($p < 0.05$). However, the effect size did not show any significant difference between the two groups for other parameters (SMDs ranged from [-0.92, 2.10] for 8-OHdG, [-3.47, 4.48] for reduced glutathione, [-1.08, 3.61] for CAT, [-5.03, 18.35] for SOD, [-2.52, 2.56] for TAC ($p > 0.05$)).

1. Introduction

X-rays and radiation emitted by radioactive sources, known as ionizing radiation (IR), are essential for diagnosing and treating diseases [1]. Every year, there are 3.6 billion radiological examinations, 37 million nuclear medicine procedures, and 7.5 million radiotherapy interventions conducted worldwide. Despite computed tomography (CT) scans, accounting for only 15 % of medical imaging procedures, they contribute a significant 75 % to the total radiation dose received by patients. It's concerning that 20 % of

Abbreviations: Advanced oxidation protein products, (AOPPs); Activator Protein 1, (AP-1); Catalase, (CAT); Glutathione, (GSH); International Commission on Radiological Protection, (ICRP); Ionizing Radiation, (IR); Malondialdehyde, (MDA); Newcastle–Ottawa Scale, (NOS); Nitrites, (NOx); Nitrogen oxides, (NOX); Nuclear Factor Kappa B, (NF-kB); Optically stimulated luminescence, (OSL); Oxidative Stress Index, (OSI); Polyunsaturated fatty acids, (PUFAs); Reactive oxygen species, (ROS); Reactive nitrogen species, (RNS); Superoxide dismutase, (SOD); Total Antioxidant Status, (TAS); Thermo Luminescent Dosimeter, (TLD); Thiobarbituric Acid Reactive Substances, (TBARS); Total Oxidant Status, (TOS); 8-Hydroxy-2′-deoxyguanosine, (8-OHdG); 8-Oxo-2′-deoxyguanosine, (8-oxodG); 8-Oxo-7,8-Dihydroguanine, (8-oxoG).

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medical radiation exposure is avoidable, and unnecessary exposure is linked to 100–250 cancer deaths annually in the UK [2,3]. The International Commission on Radiological Protection (ICRP) advises that the maximum amount of radiation exposure a person should receive is 20 mSv each year, on average over 5 years. Additionally, the ICRP states that the total radiation exposure in any given year should not exceed 50 mSv. While radiation exposure in most hospital radiology units remains below these thresholds, there is heightened risk to hospital personnel due to low, frequent, and cumulative radiation doses, especially if they fail to implement sufficient and appropriate precautions [4,5].

Reactive nitrogen species (RNS) and reactive oxygen species (ROS) are highly reactive and cause most of the tissue damage from radiation. These species have unpaired electrons and can interact with important substances in cells like DNA, proteins, and lipids, leading to changes in their functions [6,7]. When cells are exposed to radiation, the balance between oxidants and antioxidants is disrupted, causing an increase in oxidants. This leads to higher levels of antioxidants in damaged cells, helping them to either repair themselves or cell death. An antioxidant is a compound that can slow down or prevent the unwanted process of oxidation in biological substances [8,9]. Oxidative stress is linked to the development of various diseases including liver damage, cardiovascular issues, cancer, neurological disorders, and diabetes mellitus [10]. It's nearly impossible to directly measure the amounts of reactive molecules due to their very short lifespan.

The presence of oxidative stress can be assessed by measuring biomarkers such as 8-dihydro-2′-deoxyguanosine (8-oxodG), 8-hydroxy-2-deoxyguanosine (8-OHdG), advanced oxidation protein products, malondialdehyde (MDA), and hydroxynonenal, along with levels of protective antioxidants. This is important because an imbalance in redox reactions is a consequence of biological damage caused by ionizing radiation. Studies have shown variations in antioxidant and biomarker levels between exposed and unexposed groups, prompting further investigation into the correlation between occupational exposure to low levels of ionizing radiation and changes in oxygen species parameters [7,8]. Therefore, we were motivated to conduct the current systematic review and meta-analysis to examine all available evidence and determine blood oxidative stress parameters in hospital workers occupationally exposed to low doses of ionizing radiation.

2. Materials and methods

According to the PRISMA flowchart, all the desired information extracted from the articles was assembled and applied for both the systematic review and meta-analysis sections (Fig. 1). In Fig. 1, we identified 295 potentially relevant articles using a keyword search strategy. After removing 73 duplicate articles, we assessed the titles and abstracts of the remaining 222 articles. A comprehensive review of the full text of these articles led to the exclusion of 183 articles that did not meet our inclusion criteria. The reasons for exclusion were as follows: 176 articles had irrelevant study content (title and abstract), 5 articles had an unrelated method, 1 article

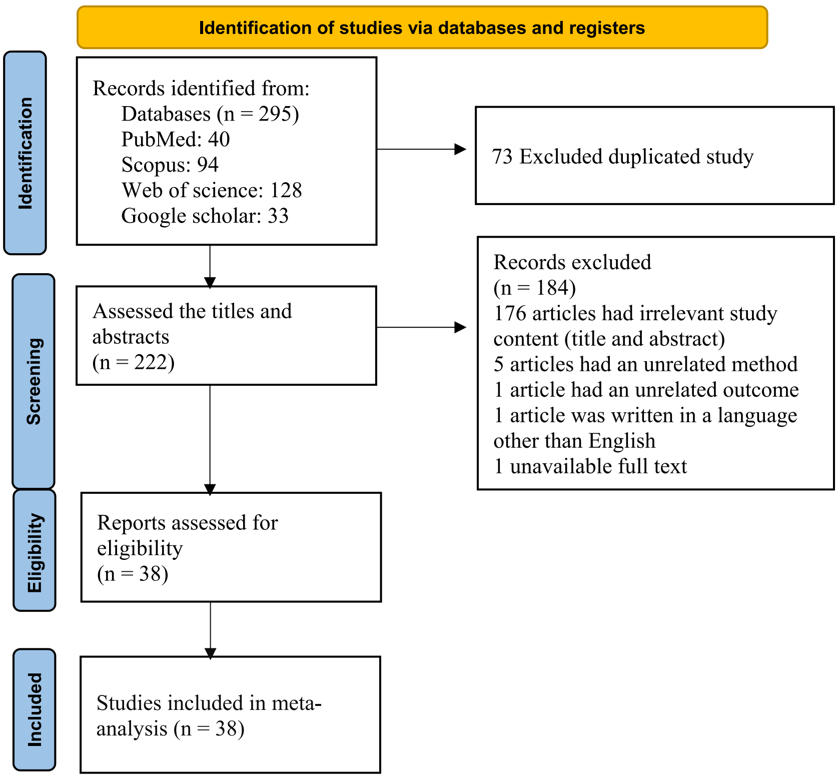

Fig. 1. PRISMA flowchart with the main steps of the research.

had an unrelated outcome, and 1 article was written in a language other than English. After thorough screening, 38 articles were included in our analysis.

2.1. Information sources and search strategy

We conducted a two-step process to screen and select studies for our systematic review. In the first step, two reviewers independently screened the titles and abstracts of records obtained from the search strategy using a predefined checklist based on eligibility

Table 1
Quality assessment of studies included in the meta-analysis: based on the Newcastle-Ottawa Scale for cross-sectional studies[a].

Papers	Selection[b]				Comparability	Outcome	Statistical test	Score
	Representativeness	Size	Non-respondents	Ascertain-ment	Design/Analysis	Assessment		
Ahmad et al. [38]	*	*	*	*	*	**	*	8
Ahmad et al. [39]	*	*	*	*	*	**	*	8
Ardiç et al. [10]	*	*	*	*	**	**	*	9
Arıcan et al. [25]	*	*	*	*	*	**	*	8
Bolbol et al. [6]	*	*	*	*	**	**	*	9
Chen et al. [34]	*	–	*	*	*	**	*	7
Doukali et al. [41]	*	*	*	*	**	**	*	9
Đurović et al. [13]	*	*	*	*	*	**	*	8
Durović et al. [14]	*	*	*	*	*	**	*	8
El-Benhawy et al. [22]	*	*	*	*	*	**	*	8
El-Eneen et al. [23]	*	-[c]	*	*	–	**	*	6
Eken et al. [27]	*	–	*	*	–	**	*	6
Eken et al. [28]	*	*	*	*	**	**	*	9
Engin et al. [29]	*	*	*	*	*	**	*	8
Fang et al. [33]	*	*	*	*	**	**	*	9
Gao et al. [5]	*	*	*	*	**	**	*	9
Gao et al. [32]	*	*	*	*	**	**	*	9
Kłucinski et al. [44]	*	*	*	*	**	**	*	9
Koc et al. [26]	*	*	*	*	**	**	*	9
Kumar et al. [17]	*	*	*	*	**	**	*	9
Kumar et al. [19]	*	*	*	*	**	**	*	9
Malekirad et al. [37]	*	*	*	*	*	**	*	8
Mrdjanović et al. [4]	*	*	*	*	**	**	*	9
Olisekodiaka et al. [43]	*	*	*	*	*	**	*	8
Rehman et al. [40]	*	–	*	*	–	**	*	6
Riahi-Zanjani et al. [36]	*	*	*	*	*	**	*	8
Russo et al. [42]	*	*	*	*	*	**	*	8
Sanaa et al. [24]	*	–	*	*	**	**	*	8
Sebastià et al. [9]	*	*	*	*	**	**	*	9
Serhatlioglu et al. [30]	*	*	*	*	**	**	*	9
Shilpa et al. [18]	*	–	*	*	–	**	*	6
Siama et al. [15]	*	*	*	*	**	**	*	9
Soylemez et al. [31]	*	*	*	*	**	**	*	9
Tawfeeq et al. [20]	*	–	*	*	–	**	*	6
Tian et al. [35]	*	*	*	*	**	**	*	9
Tričković et al. [12]	*	*	*	*	–	**	*	7
Vijayamalathi et al. [7]	*	–	*	*	–	**	*	6
Vijayamalathi et al. [16]	*	*	*	*	*	**	*	8

[a] Very Good Studies: 9–10 stars, Good Studies: 7–8 stars, Satisfactory Studies: 5–6 stars, and Unsatisfactory Studies: 0 to 4 stars.

[b] **Selection:** ***1-Representativeness of the sample:*** a. Truly representative of the average in the target population. * (all subjects or random sampling); b. Somewhat representative of the average in the target group. * (non-random sampling); c. Selected group of users/convenience sample; d. No description of the derivation of the included subjects. ***2-Sample size***: a. Justified and satisfactory (including sample size calculation). *; b. Not justified; c. No information provided. ***3-Non-respondents***: a. Proportion of target sample recruited attains pre-specified target or basic summary of non-respondent characteristics in sampling frame recorded. *; b. Unsatisfactory recruitment rate, no summary data on non-respondents, c. No information provided. ***4- Ascertainment of the exposure (risk factor)***: a. Vaccine records/vaccine registry/clinic registers/hospital records only **; b. Parental or personal recall and vaccine/hospital records. *; c. Parental/personal recall only. **Comparability:** (Maximum 2 stars) ***1-Comparability of subjects in different outcome groups on the basis of design or analysis.*** Confounding factors controlled: a. Data/results adjusted for relevant predictors/risk factors/confounders e.g. age, sex, time since vaccination, etc. **; **b.** Data/results not adjusted for all relevant confounders/risk factors/information not provided. **Outcome:** (Maximum 2 stars) ***1- Assessment of outcome***: a. Independent blind assessment using objective validated laboratory methods. **; b. Unblinded assessment using objective validated laboratory methods. **; c. Used non-standard or non-validated laboratory methods with gold standard. *; d. No description/non-standard laboratory methods used. **Statistical test:** a. Statistical test used to analyze the data clearly described, appropriate and measures of association presented including confidence intervals and probability level (p value). *; b. Statistical test not appropriate, not described or incomplete. From the explanation provided, only two parameters, "Comparability" and "Outcome" can receive two stars.

[c] The symbol "-" in the table signifies insufficient information available for evaluation.

criteria. Each record was marked as included (+), excluded (−), or unclear (*) by the reviewers based on the checklist. Records marked as included or unclear by either reviewer were then assessed in full-text screening, while records marked as excluded by both reviewers were discarded. We measured agreement between the reviewers using the Kappa statistic. In the second step, two reviewers independently evaluated the full-text articles of the selected records for eligibility using a checklist. Based on the full-text information, reviewers approved the inclusion or exclusion of each article. Articles meeting all the inclusion criteria and not meeting any of the exclusion criteria were included in the systematic review, while those not meeting the inclusion criteria or meeting none of the exclusion criteria were excluded. We recorded and reported the reasons for exclusion. The agreement between reviewers was measured using the Kappa statistic. Any discrepancies between the reviewers during the screening or selection phase were resolved through discussion and mutual agreement. If consensus was not reached, a third reviewer was consulted for the final decision. We used a PRISMA flowchart to depict the screening and selection process and the number of records at each stage.

Keywords were selected based on the Mesh Terms format and past articles, and the period was determined to February 2023 to find related case-control articles. Furthermore, articles were searched in databases separately. The pattern of finding related articles in the scientific databases was as follows: PubMed: (low[tiab] AND ionizing[tiab] AND radiation[tiab]) AND (Catalase[tiab] OR Glutathione [tiab] OR Malondialdehyde[tiab] OR lipid peroxidation[tiab] OR Superoxide[tiab] OR Superoxide dismutase[tiab] OR redox[tiab] OR antioxidant[tiab] OR oxidative stress[tiab] OR TAC[tiab] OR TAS[tiab] OR 8-OHdG[tiab]) AND (Occupation*[tiab] OR worker*[tiab] OR technician*[tiab] OR Staff*[tiab] OR Personnel*[tiab] OR Job[tiab] OR resident[tiab] OR specialist*[tiab]); Scopus and Google Scholar: (TITLE-ABS-KEY (low) AND TITLE-ABS-KEY (ionizing AND radiation) AND TITLE-ABS-KEY (catalase) OR TITLE-ABS-KEY (glutathione) OR TITLE-ABS-KEY (malondialdehyde) OR TITLE-ABS-KEY (lipid AND peroxidation) OR TITLE-ABS-KEY (superoxide) OR TITLE-ABS-KEY (superoxide AND dismutase) OR TITLE-ABS-KEY (redox) OR TITLE-ABS-KEY (antioxidant) OR TITLE-ABS-KEY (oxidative AND stress) OR TITLE-ABS-KEY (tac) OR TITLE-ABS-KEY (tas) OR TITLE-ABS-KEY (8-ohdg) AND TITLE-ABS-KEY (occupation*) OR TITLE-ABS-KEY (worker*) OR TITLE-ABS-KEY (staff) OR TITLE-ABS-KEY (personnel) OR TITLE-ABS-KEY (technician) OR TITLE-ABS-KEY (resident) OR TITLE-ABS-KEY (specialist*) OR TITLE-ABS-KEY (job)); and Web of Science: TS=(low AND ionizing AND radiation)) AND TS=(Catalase OR Glutathione OR Malondialdehyde OR lipid peroxidation OR Superoxide OR Superoxide dismutase OR redox OR antioxidant OR oxidative stress OR TAC OR TAS OR 8-OHdG)) AND TS=(Occupation* OR worker* OR technician* OR Staff* OR Personnel* OR Job OR resident OR specialist*). To prevent missing information, we attempted to identify additional publications by searching the references used in related studies.

2.1.1. Selection criteria

In hospital radiation workers included physicians, nurses, nuclear medicine technologists and radiologic technologists in the radiology, nuclear medicine, cath lab, and radiotherapy departments occupationally subjected to low-doses of low linear energy transfer (LET) ionizing radiation in the range of 20 mSv/yr (P), what is the effect of occupational exposure to ionizing radiation (I) on the blood oxidative stress parameters (O) compared with people occupationally not subjected to ionizing radiation?

2.2. Data extraction

Studies dealing with radiation of higher energies (e.g., nuclear accidents and nuclear power plant workers), studies investigating the effects of nonionizing electromagnetic radiation exposure, and in vitro and animal studies were excluded. Other types of articles, such as letters to the editor, conference and review articles, and meta-analyses, were also deleted from the publication list. The language searched in the databases was English.

2.2.1. Quality assessment

Based on the Newcastle–Ottawa Scale (NOS), the methodological quality of the included studies was evaluated (Table 1). We then assessed a study that scored five points or more as high quality, and this was according to the standards presented in previous publications; otherwise, it was considered low quality [11].

2.3. Statistical analysis

In this study, we used STATA 17.0 software to analyze the data in the meta-analysis section. We used forest plots with Hedges' g and 95 % CIs to show pooled estimates. If we found significant heterogeneity (I^2 statistic greater than 70 % and *p*-value of Q-test <0.1), we used a random-effects model for the pooled estimates; otherwise, we used a fixed-effects model. Additionally, heterogeneity of the included studies was assessed using the I-squared test (I^2) and the chi-square-based Q-test. Publication bias was evaluated using funnel plots and Egger's test or Begg's test.

3. Results

The initial search found 295 publications. After reviewing the titles and abstracts, 73 publications were considered ineligible and were therefore excluded from the study (Fig. 1). After removing duplicate entries, 222 publications remained. Out of these, 184 articles were further excluded from the study for various reasons. These reasons included the study technique not meeting the criteria (n = 5), the articles not being written in English (n = 1), the articles lacking the outcome of interest (n = 1), and the full text of the articles not being available (n = 1), and after reading the titles and abstracts (n = 176). In total, 38 articles were included in the study.

3.1. Study characteristics

Four studies originated from Serbia [5,12–14], seven from India [6,7,15–19], one from Iraq [20,21], three from Egypt [22–24], eight from Turkey [10,25–31], one from Spain [9], five from China [5,32–35], two from Iran [36,37], two from the USA [38,39], one from Pakistan [40], one from Tunisia [41], one from Italy [42], one from Nigeria [43], and one from Poland [44]. In total, 3514 workers with an overall age range of 18–67 years were included in this review (Table 2). Personal dosimeters were used to assess the amount of exposure. Eleven, four, and one of thirty-eight studies reported thermoluminescent dosimeters (TLDs) [5,12–15,17,19,28,32,33,39], film badges [12,14,18,34] and optically stimulated luminescence (OSL) [25], respectively, as the type of dosimeter. Of the thirty-eight studies included in the review, twenty-nine articles addressed radiation work experience for hospital workers. The main characteristics of the included studies are described in Table 2.

3.2. Quality assessment of the selected studies

3.2.1. Dose

Out of the articles we reviewed, 25 of them included personal dosage records. However, only a few of these articles specified the type of dosimeter used [5,13,14,39], as shown in Table 2. Due to the variability in the reported dose values, we were unable to categorize the studies based on dose. It's important to note that all individual effective doses remained within the permitted limits suggested by the ICRP.

3.3. Study outcomes

The majority of research has shown a significant difference in blood oxidative stress markers between hospital radiation workers and a control group. The impact of radiation exposure on blood oxidative stress parameters varied among hospital radiation workers. Several studies [6,9,10,13–15,24,33,34,38] have highlighted a significant connection between blood oxidative stress biomarkers, work duration, employees in different imaging departments, the number of daily attended patients, and personal effective dose (Table 3). Changes in the values of oxidative stress parameters such as nitrites (NOx) [9], reduced glutathione (GSH)/oxidized glutathione (GSSG) [9], thiobarbituric acid reactive substances (TBARS) [9], total antioxidant capacity (TAC) [9], extracellular superoxide dismutase (EC-SOD) [9], superoxide dismutase (SOD) [39], GSH [23], advanced oxidation protein products (AOPPs) [23], MDA [23,39], thiol [25], 8-OHdG [32], and $O_2\bullet^-$ [39] differed in workers from different imaging departments. Correlations between some oxidative stress parameters, such as GSH [17,35], SOD [6], MDA [6,14], CAT [15], 8-OHdG [24,32,34], 4-hydroxynonenal (4-HNE) [34], TAC [17], and $O_2\bullet^-$ [39], and radiation dose values were found. Correlations were discovered between oxidative stress parameters, including SOD [5,33], MDA [6,7,16,28,33], total antioxidant status (TAS) [7,10,16], total oxidant status (TOS) [10], CAT [15], 8-OHdG [32], thiol [26], $O_2\bullet^-$ [39], and exposure duration.

3.3.1. Reactive species

The plasma levels of nitrogen oxides (NOx) in the exposed groups ($n = 2$) were statistically significantly increased compared to the healthy control group [9,29]. The study findings indicated a considerable increase in the level of superoxide ($O_2\bullet^-$) in the entire blood of the exposed group compared to the control patients [38,39]. The findings did not reveal any statistically significant variations in the levels of reactive oxygen species (ROS) [42]. The patients who were exposed demonstrated a threefold elevation in hydrogen peroxide levels [42].

3.3.2. Total oxidant

Total oxidant status (TOS) ($n = 1$) [10] and oxidative stress index (OSI) [TOS/total antioxidant status (TAS)] ($n = 2$) [10,31] values were significantly higher in the exposed group than in the control group ($p < 0.01$).

3.3.3. Metabolic oxidation products

3.3.3.1. Lipid oxidative damage markers. Two different studies illustrated increased levels of lipid peroxidation by-products in hospital workers in X-ray and radiology units who are exposed to chronic low-dose radiation, respectively [12,37]. MDA levels ($n = 12$) were higher in the exposed group than in the control group [4–7,14–16,22,23,30,39,41]. Another study reported increased levels of 4-HNE [34]. However, three studies [27,28,33] showed a reduction in MDA levels. Additionally, statistical analysis from four trials [17–20] did not demonstrate a significant difference in MDA levels between the two groups. The findings indicated a notable increase in thiobarbituric acid reactive substances (TBARS) levels in the nuclear medicine group compared to the non-exposed group. Conversely, the interventional radiology and cardiology group exhibited a significant decrease in TBARS levels compared to the non-exposed group [9].

3.3.3.2. DNA oxidative damage markers. A study reported a significant increase in the 8-oxodG value in comparison with controls [12]. This finding revealed that serum 8-OHdG levels increased with increasing radiation dose and working period [32]. Higher levels of 8-OHdG ($n = 2$) were reported compared to controls [24,34]. 8-OHdG levels within control subjects and all radiation-exposed workers revealed no significant differences [38].

Table 2
The most important information extracted from the studies for both systematic review and meta-analysis sections.

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
Ahmad et al. [38]	8	Exposed: 3 M Control: 5 M Exposed: 17 F Control: 35 F	Exposed: Healthy workers from Conventional Radiography (CR), Interventional Radiography (InR), and CT departments Control: Unexposed individuals	Exposed: 39.4 ± 2.2 Control: 41.1 ± 1.8	Mean: 16 ± 2 (yr)	lifetime effective doses (mSv): CR: 17.09 ± 5.73 InR: 31.00 ± 16.17 CT: 45.98 ± 11.32 Annual effective dose (mSv): 2.03 ± 0.4	Superoxide (O_2^-)	___	Blood plasma	USA
Ahmad et al. [39]	8	Exposed: 3 M Control: 5 M Exposed: 17 F Control: 35 F	Exposed: Healthy technologists from CR, CT and InR units Control: Healthy unexposed individuals	Exposed: 39.4 ± 2.19 Control: 41.1 ± 1.8	3-34 (yr) 16 ± 2 (yr)	0.05–6.35 2.03 ± 0.4 (mSv/yr) Lifetime effective doses (mSv) TLD CR: 17.09 ± 5.73 InR: 31.00 ± 16.17 CT: 45.98 ± 11.32	$O_2^{\bullet -}$ MDA SOD activity	___	Blood plasma/ Erythrocyte	USA
Ardiç et al. [10]	9	Exposed 43 M Control 36 M Exposed 43 F Control 50 F	Exposed: workers of radiology, nuclear medicine, radiation oncology, Interventional radiology Control: Unexposed subjects	Exposed: 35.91 ± 7.0 7 control: 34.96 ± 8.25	Mean: 9.80 ± 7.18		TOS: (7.15 ± 4.34 vs. 5.24 ± 3.60 micmol H_2O_2 Eq/L) OSI: (0.68 ± 0.60 vs 0.39 ± 0.38)	TAS: (1.37 ± 0.40 vs 1.75 ± 0.50 mmol Trolox Eq/L)	Blood serum	Turkey
Arıcan et al. [25]	8	Exposed: 37 M Control: 33 M Exposed: 8 F Control: 12 F	Exposed: outside the operating room subgroup (workers of Interventional radiology) and inside the operating room subgroup Control: Healthy unexposed subjects	Exposed: 36.11 ± 6.30 Control: 34.73 ± 6.59	Outside[a]: 5.30 ± 2.40 inside[a]: 6.61 ± 5.14	Personal dose equivalent during 1 year (mSv) OSL[a] outside: 0.63 ± 0.52 inside: 0.21 ± 0.04	___	Native Thiol (micmoL/L): (487.60 ± 62.91) vs (541.41 ± 69.48) Total thiol (micmoL/L): (556.64 ± 61.60) vs (607.64 ± 71.36)	Blood plasma	Turkey
Bolbol et al. [6]	9	Exposed: 14 M Control: 9 M Exposed: 17 F Control: 22 F	Exposed: Healthy workers from DR department Control: Healthy unexposed workers	Exposed: 24–55 35 ± 6.9 Control: 20–56 36.7 ± 9.5	5–30 12.39 ± 6.16 (yr)	Annual effective dose (mSv): 0.21–0.27 0.23 ± 0.02	MDA (nmol/mL): 24.72 ± 3.64 vs 14.27 ± 1.34	SOD (U/mL): 9.89 ± 4 vs 20.49 ± 2.7	Blood plasma	India
Chen et al. [34]	7	Exposed: 117 Control: 117	Exposed: Interventional physicians Control: Nonexposed workers from Bmode ultrasound, electrocardiogram, and	Exposed: 28-50 38.95 ± 5.92 Control: 27–53	7.92 ± 3.57 (yr)	Annual effective dose (mSv): 2.333 ± 1.052	8-OHdG (ng/mL): 3.014 ± 1.34 vs 2.635 ± 1.28 4-HNE (ng/mL): 13.36 ± 3.78 vs 12.43 ± 3.26	___	Blood serum	China

(continued on next page)

Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
			other auxiliary medical departments	40.03 ± 6.93						
Doukali et al. [41]	9	Exposed: 11 M Control: 98 M Exposed: 18 F Control: 56 F	Exposed: Workers from Radiotherapy and radiology departments Control: Healthy subjects	Exposed: 27–58 43.52 ± 8.89 Control: 20–60 37.50 ± 11	3–33 14.65 ± 7.22 (yr)		MDA (nmol/g HB): 25.35 ± 1.99 vs 10.94 ± 0.17 CAT(μmol H_2O_2 degraded/min/mg HB): 11.78 ± 0.37 vs 6.17 ± 1.01 SOD (units/mg HB): 6.73 ± 0.20 vs 2.59 ± 0.13	___	Erythrocyte	Tunisia
Durović et al. [14]	8	Exposed: 29 M Control: 23 M Exposed: 15 F Control: 10 F	Exposed: Healthy workers in Radiology and nuclear medicine unit Control: Healthy unexposed subjects	Exposed: 32–55 43.3 ± 6.01	Rad staff: 5–27 15.00 ± 5.97 (yr) NM staff: 5–23 14.92 ± 5.21 (yr)	Annual effective dose (mSv) TLD Rad staff: 2.87 ± 2.78 NM staff: 0.71 ± 0.56	MDA (nmol/ml): 9.49 ± 3.16 vs 6.21 ± 2.67	___	Blood	Serbia
El-Benhawy et al. [22]	8	Exposed 50 F Control 50 F	Exposed: Radiation workers Control: Healthy unexposed subjects	Exposed: 30–48 34.36 ± 5.07 Control: 25–50 33.90 ± 4.55	6-19 11.57 ± 3.85 (yr)	Annual effective dose (mSv) film badge 2.2–10.0 3.64 ± 1.68	MDA (nmol/mL): 5.95 ± 2.89 vs 1.80 ± 0.69	TAC (mM/L): 0.87 ± 0.22 vs 1.62 ± 0.16	Blood serum	Egypt
El-Eneen et al. [23]	6	Exposed: 50 Control: 50	Exposed: Workers from conventional radiology (CR), interventional radiology (InR) and CT scan departments Control: Healthy unexposed workers	Exposed: 31–54 41.6 ± 5.7 Control: 41.9 ± 4.8	10–31 20.3 ± 5.4 (yr)	Annual effective dose (mSv) 0.05–5.5 1.00 ± 1.36	MDA (nmol/ml): 3.40 ± 0.93 vs 1.72 ± 0.63 AOPPs (μmol/L): 131.52 ± 106.65 vs 46.95 ± 18.02	GSH (mmol/L): 0.02 ± 0.02 vs 0.14 ± 0.20	Blood plasma	Egypt
Eken et al. [27]	6	Exposed: 40 Control: 30	Exposed: Healthy physicians and technicians of radiology unit Control: Healthy nonexposed volunteers	___	1–30 yr 5 h/day 0.10–3.86	Film badge 0.32 ± 0.69 (mSv/month)	CuZn-SOD Se-GPx	CAT MDA	Erythrocyte	Turkey
Eken et al. [28]	9	Exposed: 26 M Control: 20 M Exposed: 14 F Control: 10 F	Exposed: Healthy personnel from radiology unit Control: Healthy unexposed volunteers	Exposed: 27–58 Control: 25–57	1–30 yr	TLD 0.10–3.86 (mSv per month)	CuZn-SOD [U/g Hb]: 2038 ± 288 vs 1389 ± 368 Se-GPx [U/g Hb]: 26 ± 5 vs 21 ± 6	CAT [KU/g Hb]: 331 ± 60 vs 370 ± 84 MDA: [nmol/g	Erythrocyte	Turkey

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Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
								Hb] 76 ± 22 vs 115 ± 26		
Engin et al. [29]	8	Exposed: 12 M Control: 7 M Control: 15 F Exposed: 41 F	Exposed: Workers from Radiotherapy and Radiology units Control: Healthy unexposed subjects	RT staff: 28.6 ± 0.72 RD staff: 31.7 ± 0.77 Control: 28.7 ± 0.83	RT staff: 6.51 ± 0.85 yr (5 h/day) RD staff: 11.2 ± 0.80 yr (5 h/day)		NOx (micmol/l) RT: 27.2 ± 2.54, RD: 40.8 ± 4.64 Vs control: 19.2 ± 2.33	___	Blood plasma	Turkey
Fang et al. [33]	9	Exposed: 119 M Control: 111 M Exposed: 56 F Control: 48 F	Exposed: Healthy workers of interventional and diagnostic radiology departments Control: Healthy nonexposed workers	Exposed: 38.3 Control: 36.6	1-31 (yr)	TLD 2.81–416.43 38.41 + 27.36 (mSv)	___	MDA SOD	Blood serum	China
Gao et al. [5]	9	Exposed: 142 M Control: 86 M Exposed: 76 F Control: 32 F	Exposed: workers from diagnostic radiology, radiotherapy, interventional radiology and nuclear medicine departments Control: healthy nonexposed volunteers	Exposed: 20–67 Control: 23–64		The median value of annual effective dose TLD: 0.48 (mSv) interquartile range: 0.35–0.67 (mSv)	[M,Q1,Q3] MDA (nmol/ml): 3.6 (1.8,5.9) vs 1.8 (1.05,2.7) CAT (U/mgHb): 8.97 (6.80,10.7) vs 5.8 (4.4,8.1) CuZn SOD (U/ml): 30.4 (26.03,33.2) vs 28.8 (27.4,30.98)	___	Blood plasma	China
Gao et al. [32]	9	Population Study: 230 radiation workers (108 M and 122 F)	Exposed: diagnostic radiology (n = 75); Radiotherapy (n = 60); nuclear medicine (n = 41); interventional radiology (n = 54)	31–51 37.90 ± 4.45 (yr)	Radiation workers: 9.87 ± 5.54 (yr) DR: 12.28 ± 4.91 (yr) RT: 9.22 ± 5.85 (yr) NM: 8.93 ± 6.28 (yr) InR: 7.94 ± 4.20 (yr)		OHdG levels of the DR, RT, NM, and InR groups were 80.93 ± 23.71, 91.44 ± 32.98, 95.63 ± 34.83, and 120.29 ± 63.88	___	Blood serum	China

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Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
Kłucinski et al. [44]	9	Exposed: 14 M Control: 12 M Exposed: 31 F Control: 18 F	Exposed: Healthy workers of X-ray departments Control: Healthy unexposed individuals	Exposed: 25–54 44.5 (yr) Control: 28–61 40.4 (yr)	2–33 15.3 (yr)	Annual effective dose: <1 mSv/yr	___	SOD (U/g of Hb): 959.4 ± 198.8 vs 1154.7 ± 272.4 GPx (U/g of Hb): 29.1 ± 3.6 vs 39.4 ± 6.6 CAT (U/g of Hb): 270.4 ± 54.7 vs 301.8 ± 57.1	Erythrocyte	Poland
Koc et al. [26]	9	Exposed: 34 M Control: 19 M Exposed: 29 F Control: 26 F	Exposed: Healthy staff of Interventional cardiology and Interventional radiology and nuclear medicine Control: Healthy nonexposed workers	Exposed: 18-49 33.67 ± 7.7 (yr) Control: 21–52 33.62 ± 6.3 (yr)	The average dosimeter results during the last 3 months	In-cardiology group: 0.46 (mSv) InR group: 0.40 (mSv) NM group: 0.47 (mSv)	___	native thiol (micmol/l): 528.96 ± 86.42 vs 561.05 ± 104.83	Blood serum	Turkey
Kumar et al. [17]	9	Exposed: 83 M Control: 51 M	Exposed: Healthy staff of radiology, radiotherapy, and nuclear medicine Control: nonexposed participants	Exposed: 27.74 ± 0.75 Control: 28.03 ± 0.83	6.51 ± 0.66 yr	cumulative radiation exposure level TLD (Low and high absorbed dose subgroup): LAD ≤0.05 HAD > 0.05	Total GSH (mmol/L): 2.507 ± 0.09 vs 2.044 ± 0.07 Oxidized GSH (mM): 0.746 ± 0.06 vs 0.527 ± 0.03 TAC (mmol/L): 1.764 ± 0.05 vs 1.480 ± 0.047 SOD (units/μL): 0.0344 ± 0.00 vs 0.0242 ± 0.001	___	Blood plasma	India
Kumar et al. [19]	9	Exposed: 83 M Control: 51 M	Exposed: Healthy diagnostic radiology and radiotherapy staff Control: Healthy unexposed individuals	Exposed: 27.7 ± 0.7 Control: 28 ± 0.8	6.51 ± 0.66 (yr)	Cumulative radiation exposure level TLD: LAD <0.05 HAD > 0.05	Total GSH (mM): 1.29 ± 0.06 vs 1.02 ± 0.05 reduced GSH (mM): 0.98 ± 0.05 vs 0.67 ± 0.06 TAC (mM): 4.49 ± 0.13 vs 3.388 ± 0.14	___	Seminal plasma	India
Malekirad AA. 2005	8	Exposed: 17 M Control: 18 M Exposed: 15 F Control: 19 F	Exposed: Healthy workers in Radiology unit Control: Healthy unexposed subjects	Exposed: 36.1 ± 9.9 Control: 32.9 ± 9.2	13.5 ± 9 (yr)		Lipid Peroxidation TAC Thiol groups	___	Blood plasma	Iran

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Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
Mrdjanović et al. [4]	9	Exposed: 21 M Control: 10 M Exposed: 30 F Control: 14 F	Exposed: Radiotherapy workers Control: Healthy unexposed subjects	Exposed: 24-61 control: 23–68	8-21 (yr)	Irradiation during one year (mSv): Median: 2.06 Range: 1.70–3.02	CAT (U/g Hgb): 2888 vs 2137 MDA (nmol/L): 2.64 vs 1.81	___	Blood plasma	Serbia
Olisekodiaka et al. [43]	8	Exposed: 16 M Control: 14 M Exposed: 7 F Control: 12 F	Exposed: Healthy workers in Radiology unit Control: Healthy unexposed individuals	Exposed: 34.85 ± 5.25 Control: 32.19 ± 9.12	___		___	___	Blood serum	Nigeria
Rehman et al. [40]	6	Exposed: 50 Control: 20	Exposed: Healthy volunteers X-ray technicians Control: Unexposed healthy individuals	___	8–12 h/day for six days per week		Protein carbonylation	Total thiol	Blood serum	Pakistan
Riahi-Zanjani et al. [36]	8	Exposed: 24 M Control: 15 M Exposed: 16 F Control: 15 F	Exposed: Healthy radiology staff Control: Healthy unexposed individuals	Exposed: 37.48 ± 2.1 Control: 35.55 ± 1.9	13.68 ± 1.7 (yr)		___	___	Blood serum	Iran
Russo et al. [42]	8	Exposed: 10 M Control: 8 M Exposed: 0 F Control: 2 F	Exposed: Healthy interventional Cardiologists Control: Healthy unexposed workers	Exposed: 38 ± 5 Control: 35 ± 3	3–9 10 ± 6 (yr)	last year radiation exposure TLD: 1.2–8.3 4.7 ± 3.2 (mSv/yr)	GSH (Mm): 20.61 + 2.16 vs 12.37 + 1.22 FOx assay (micmol H_2O_2 Eq): 6.51 ± 1.55 vs 2.21 ± 1.03	Cu,Zn-SOD	Erythrocyte/ Blood plasma/ Blood serum	Italy
Sanaa et al. [24]	8	radiotherapy group: 20 diagnostic radiology group: 20 Control: 30	Exposed: Healthy workers from RT and DR departments Control: Healthy unexposed volunteers	RT group: 36.25 ± 6.70 DR group: 31.65 ± 7.58 Control: 33.53 ± 7.27	RT group: 11 ± 7.60 (yr) DR group: 9 ± 6.90 (yr)	Annual effective dose (mSv) Film badge DR group: 2.93 ± 1.91 1.5–4.5 RT group: 3.13 ± 1.46 1.5–6	8-OHdG level (ng/ml) in DR and RT groups: 4.61 ± 2.62, 4.69 ± 2.60 vs control 1.50 ± 0.71	___	Blood serum	Egypt
Sebastià et al. [9]	9	Exposed: 12 M Control: 10 M Exposed: 30 F Control: 18 F	Exposed: workers from the Interventional Radiology and Cardiology (G1), Radiation Oncology (G2), Nuclear Medicine (G3) Service. Control: Healthcare	G1: 48 ± 1 G2: 50 ± 3 G3: 48 ± 1 Control: 43 ± 2		Personal dose equivalent during 1 year (mSv): 0.0–1.9 0.2 ± 0.07 G1: 0.0–1.9 0.22 ± 0.15 G2: 0.0–0.6	NOX GSH/GSSG TBARS (**G3**)	TAC Ec-SOD (**G1, G3**) TBARS (**G1**)	Blood plasma	Spain

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Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
			Workers nonexposed to ionizing radiation			0.05 ± 0.03 G3: 0.0–1.4 0.45 ± 0.17				
Serhatlioglu et al. [30]	9	Exposed: 26 M Control: 19 M Control: 8 F Exposed: 25 F	Exposed: Healthy workers in diagnostic radiology Control: Healthy unexposed volunteers	Exposed: 34.4 ± 7.07 Control: 38.3 ± 6.9	___		MDA (nmol/ml): 0.74 0.17 vs 0.57 0.13	___	Blood serum	Turkey
Shilpa et al. [18]	6	Exposed (Diagnostic Radiology): 40 Control: 40	Exposed: Healthy workers of DR Control: Healthy unexposed individuals	Exposed: 22–38 (yr)	___		___	___	Blood plasma/ Erythrocyte	India
Siama et al. [15]	9	Exposed: 22 M Control: 18 M Exposed: 11 F Control: 15 F	Exposed: Healthy radiology technicians Control: Healthy unexposed volunteers	Exposed: 36.87 ± 1.86 Control: 32.15 ± 2.16	3–29 10.33 ± 7.05 (yr) Patients handled per day: 15.54 ± 0.81	The cumulative effective Dose (mSv) **TLD**: 3.14–144.5 40.88 ± 39.86	MDA	GST CAT	Blood plasma	India
Soylemez et al. [31]	9	Exposed: 18 M Control: 17 M Exposed: 27 F Control: 23 F	Exposed: Healthy radiology technicians Control: Healthy unexposed workers	Exposed: 39.93 ± 9.31 Control: 39.65 ± 6.26	14.24 ± 7.73 (yr)	<3.8 (mGy/month)	Oxidative stress index (OSI): 20.69 ± 15.51 vs 5.57 ± 7.25	___	Blood serum	Turkey
Tawfeeq et al. [20]	6	Exposed: 16 Control: 16	Exposed: X-ray technicians Control: Healthy unexposed subjects	Exposed: 24–52	1–22 years	-Most technicians worked for up to 6 h a day for 5 days per week, A minority of them worked for 3 days per week	___	GSH	Blood serum	Kurdistan Region, north of Iraq
Tian et al. [35]	9	Exposed: 60 M Control: 46 F	Workers of radiology, nuclear medicine, radiotherapy and interventional radiology	24–58 37.48 (yr)	1–39 11.30 ± 10.36 (yr)	annual effective dose (mSv): 0.09–10.71 0.58 ± 1.18	GSH (nmol/mL) based on dosage groups: 0–0.3 (mSv/yr); 401.32 ± 218.02 0.3–0.4 (mSv/yr); 539.13 ± 771.50 0.4–0.5 (mSv/yr); 702.08 ± 546.63	___	Erythrocyte	China
Tričković et al. [12]	7	Exposed: 8 M Control: 7 M Exposed: 26 F Control: 23 F	Exposed: Radiologists and technicians exposed to diagnostic X-rays Control: Healthy unexposed participants	Exposed: 35.3 ± 8.2 control: 39.5 ± 6.8	20.2 ± 4.2 (yr)	Annual TLD dose (mSv): 5.2 ± 3.6	LPP 8-oxo dG	___	Blood plasma	Serbia

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Table 2 (*continued*)

Author [Ref.]	NOS score	Participant (n) Male/Female	Group	Mean Age (Year; Mean ± SD)	Work experience with radiation (Year; Mean ± SD)	Personal dose (mSv)	Increase (mean ± SD Exposed vs. mean ± SD Unexposed)	Decrease (mean ± SD Exposed vs. mean ± SD Unexposed)	Sample	Country
Vijayamalathi et al. [7]	6	39 volunteers	Exposed: Radiographers Control: Unexposed participants	___	Up to 14 years		MDA TAA	___	Blood serum	India
Vijayamalathi et al. [16]	8	Exposed: 37 M Control: 40 M	Exposed: Radiographer Control: Unexposed volunteers	Exposed: 20–36	___		TAA MDA	___	Blood serum	India

TLD = Thermoluminescent dosimeter; 8-oxo-dG = 8-hydroxydeoxyguanosine; LPP = lipid peroxidation product; CAs = chromosomal aberrations; PAB = pro-oxidant antioxidant balance; GSH = glutathione; OSI = oxidative stress index; MDA = malondialdehyde; SOD = superoxide dismutase; TAA = total antioxidant activity; CAT = catalase; TAC = total anti-oxidant capacity; TOS = total oxidant status; TAS = total anti-oxidant status; NO_X = nitrogen oxides; GSSG = oxidized glutathione; TBARS = thiobarbituric acid reactive substance; Ec-SOD = extracellular-SOD; GSH-Px = Plasma glutathione peroxidase; GPx = glutathione peroxidase; AOPPs = advanced oxidation protein products; GST = glutathione S-transfrase; OHdG = 8-hydroxyguanosine; HB = hemoglobin; ROS = reactive oxygen species; Optically Stimulated Luminescence (OSL) dosimetry technique; inside the operating room; outside the operating room; 4-HNE = 4-Hydroxynonenal; Mn = manganese; Cu = copper; Zn = zinc; Se = selenium.

[a] Sort by alphabet.

Table 3
Outcome reported by each of the reviewed studies.

Author [Ref.]	outcome
Ahmad et al. [38]	- Significant: Superoxide - The values of 8-OHdG (3.97 ± 0.27 vs. 4.51 ± 0.40 ng/ml) and EcSOD (183.1 ± 31.1 vs. 240.4 ± 41.5 U/mL EcSOD) as well as the GSH/GSSG ratio in both control subjects and radiation exposed workers showed no significant differences (p > 0.05).
Ahmad et al. [39]	- Non-significant: CAT; GSH; GSH/GSSG - The levels of $O_2^{\bullet -}$ and MDA, as well as the SOD activity in the blood of subjects exposed to InR and CT, were considerably greater compared to both the subjects exposed to CR and the control individuals ($p < 0.05$). However, there were no significant differences observed between the subjects exposed to CR and the control individuals ($p > 0.05$). - The levels of $O_2^{\bullet -}$ showed a positive correlation with both the lifetime effective radiation dose and the years of occupational radiation exposure.
Ardiç et al. [10]	- Significant: TOS; OSI; TAS[a] (TOS/TAS) - Within the IR group, there was a significant negative correlation between the duration of employment and the TOS and OSI values (r = −0.283, p = 0.008 and r = −0.265, p = 0.014, respectively). Additionally, there was a significant positive correlation between the duration of employment and the TAS value (r = 0.241, p = 0.026).
Arıcan et al. [25]	- Significant: Native thiol; Total thiol Non-significant: disulfide - Additionally, the group exposed to radiation outside the operating room had considerably lower values of native thiol and total thiol compared to the group inside the operating room (p = 0.028, p = 0.019, respectively).
Bolbol et al. [6]	- Significant: MDA; SOD - The results indicated a strong negative correlation between the level of SOD, duration of work (p = −0.95, r = 0.03), and environmental exposure (p = −0.90, r = 0.04). Conversely, there was a significant positive correlation between the level of MDA, duration of work (p = 0.88, r = 0.04), and environmental exposure (p = 0.89, r = 0.04) in the exposed group.
Chen et al. [34]	- Significant: 8-OHdG; 4-HNE - The annual amount of radiation exposure in interventional physicians showed a direct relationship with the levels of 8-OHdG (r = 0.274, p = 0.003) and 4-HNE (r = 0.384, p = 0.000).
Doukali et al. [41]	- Significant: MDA; CAT; SOD - Non-significant: GPx; AOPP[a] - The exposed participants exhibited a 12 % increase in GPx activity compared to the controls; however this difference was not statistically significant. - No effect of duration of exposure was noted, neither on the oxidant biomarkers nor on the antioxidant enzyme's activities.
Durović et al. [14]	- Significant: MDA - Lipid peroxidation index is significantly correlated with doses. - The difference between controls and subgroups was statistically significant too (p = 0.0001 for Rad and p = 0.018 for NM), while it was not significant between subgroups (p = 0.54).
El-Benhawy et al. [22]	- Significant: MDA; TAC
El-Eneen et al. [23]	- Significant: GSH; MDA; AOPPs - The lowest levels of erythrocyte GSH observed in the InR[a] subgroup. - A notable difference was seen between the CR and InR subgroups (0.03 ± 0.02 and 0.01 ± 0.01 mmol/L, respectively, p = 0.037), although no significant distinctions were detected between the CT versus CR and InR categories ($p > 0.05$). - A notable difference was noted between the InR subgroup and the CR and CT subgroups in terms of the plasma levels of MDA and AOPPs, with values of 4.7 ± 0.27, 2.6 ± 0.38, and 3.90 ± 0.40 nmol/ml, and 302.25 ± 7.50, 62.00 ± 19.23, and 147.89 ± 80.33 μmol/L, respectively ($p < 0.01$).
Eken et al. [27]	- Significant: CuZn-SOD; Se-GPx; CAT; MDA
Eken et al. [28]	- Significant: CuZn-SOD; Se-GPx; CAT; MDA - An almost significant association between years of employment and MDA level was seen in the exposed group (p = 0.069).
Engin et al. [29]	- Significant: NOx - There was no significant difference between the radiation-exposed groups ($p > 0.05$).
Fang et al. [33]	- The findings suggest a correlation between the levels of serum MDA and SOD activity and the length of exposure to low-dose ionizing radiation. - The levels of MDA and SOD in workers who had been exposed to low-dose ionizing radiation for over 20 years were significantly lower compared to the control group ($p < 0.05$, $p < 0.01$ respectively). - There was no significant correlation between the level of GSH and the duration of X-ray exposure.
Gao et al. [5]	- Significant: CuZn-SOD; CAT; MDA - Non-significant: GSH-Px
Gao et al. [32]	- Job classification, dose (mSv), and working period (year) partly affected serum 8-OHdG levels ($p < 0.001$). - The levels of serum 8-OHdG were considerably elevated in the InR group compared to the DR, RT, and NM groups ($p < 0.05$).
Kłucinski et al. [44]	- Significant: GPx; SOD; CAT - Activity of SOD was significantly higher in smoking workers in comparison to non-smoking subjects exposed to radiation ($p < 0.05$).
Koc et al. [26]	- Significant: native thiol - Non-significant: total thiol; disulphide - Native thiol, total thiol, and disulphide concentrations evaluated according to exposure duration (1–5, 6–10, > 10 yr) and exposure distance (1m, 2m, working around) revealed no significant differences ($p > 0.05$)
Kumar et al. [17]	- Significant: Total GSH; oxidized GSH; TAC; SOD - Non-significant: decreased GSH; MDA - While the exposed group exhibited higher levels of decreased GSH compared to the nonexposed group, the observed difference did not reach statistical significance. - The diminished GSH level in the HAD group exhibited a statistically significant increase compared to the nonexposed patients ($p < 0.05$). - Furthermore, the TAC levels in the HAD[a] group were substantially greater than those in the LAD[a] group ($p < 0.05$).

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Table 3 (*continued*)

Author [Ref.]	outcome
Kumar et al. [19]	- Significant: Total GSH; reduced GSH; TAC - Non-significant: SOD; MDA
Malekirad AA. 2005	- Significant: Lipid peroxidation; TAC; Thiol groups - No linear correlation between years of employment was seen with other components of oxidative stress.
Mrdjanović et al. [4]	- Significant: CAT; MDA
Olisekodiaka et al. [43]	- Non-significant: TAS
Rehman et al. [40]	Significant: Protein carbonylation; Total thiol
Riahi-Zanjani et al. [36]	The mean TAL[a] level of radiology staff (833 ± 30.4 μmol/L) was lower than control group (875 ± 46.8 μmol/L), however the difference was not statistically significant (p = 0.546).
Russo et al. [42]	- Significant: Cu,Zn-SOD; GSH; FOX - Non-significant: ROS; serum TAC; CAT activity
Sanaa et al. [24]	- Significant: 8-OHdG[a] - There was insignificant difference in serum 8-OHdG between radiotherapy and diagnostic radiology groups (P = 0.625). - There was a strong correlation between the total yearly radiation exposure and the levels of 8-OHdG in the blood serum ($p < 000$). - The correlation between working period with serum 8-OHdG concentration was not the statistically significant (P = 0.153).
Sebastià et al. [9]	- Significant: TAC; NOx - The activity of Ec-SOD showed a tendency to decrease in group 3 and group 1 (p = 0.1 and p = 0.16, respectively) when compared to the group that was not exposed. - The GSH/GSSG ratio exhibited a statistically significant increase in groups 1 and 2 (p = 0.023 and p = 0.031, respectively). The increase observed in group 3 was nearly significant (p = 0.084). - A significant increase of TBARS was observed in group 3 (p = 0.008) compared to non-exposed group. - The levels of TBARS exhibited a substantial decrease in group 1 (p = 0.015) as compared to the non-exposed group. - The levels of NOx showed a substantial rise in group 2 (p = 0.002) and a somewhat less significant increase in group 3 (p = 0.054) compared to the non-exposed group. - The findings indicated that Groups 2 and 3 had a significant likelihood of being part of the high oxidative stress group (p = 0.048, p = 0.01, respectively). The probability of group 1 belonging to high oxidative stress was marginally significant but did not reach statistical significance (p = 0.133).
Serhatlioglu et al. [30]	Significant: MDA
Shilpa et al. [18]	- MDA [565.98 ± 116.86 vs. 552.82 ± 113.36 (nmol/100 ml RBC)], CAT [418976 ± 219944 vs. 313167 ± 117415 (units/g Hb)] and vitamin E [8.38 ± 2.16 vs. 7.68 ± 1.58 (mg/L)] levels were slightly increased in tests when compared to the controls; however the differences were not statistically significant.
Siama et al. [15]	- Significant: MDA; GST[a]; CAT - The radiology technicians with over 10 years of experience working with X-rays, who have been exposed to a cumulative effective dose of over 50 mSv ($p < 0.01$), and who handle more than 15 patients per day ($p < 0.05$), exhibited a notable decrease in CAT activity compared to occupational workers with less than or equal to 10 years of experience handling X-rays, who received a cumulative effective dose of less than or equal to 50 mSv, and who handle less than or equal to 15 patients per day during their employment.
Soylemez et al. [31]	- Significant: OSI
Tawfeeq et al. [20]	- Significant: GSH - Non-significant: MDA
Tian et al. [35]	- There was no statistically significant variation in the concentration of GSH among different types of job and length-of-service groups. A considerable statistical difference was seen in the GSH levels across different dosage groups. An upward trend in GSH concentration was detected when the annual effective dose increased, ranging from 0 mSv to 0.5 mSv ($p < 0.01$).
Tričković et al. [12]	- Significant: 8-oxo-dG; LPP[a] - Non-significant: PAB[a] - Exposed participants with CAs[a] and those without CAs showed significantly higher lipid peroxidation product levels than controls ($p < 0.05$ and $p < 0.001$, respectively).
Vijayamalathi et al. [7]	- Significant: MDA - Radiographers who were exposed to ionizing radiation for 7–14 years showed a slight increase in MDA levels compared to those exposed for less than 7 years. - Workers exposed for 7–14 years exhibited a marginal decline in antioxidant level compared to workers exposed for less than 7 years.
Vijayamalathi et al. [16]	- Significant: MDA - An observed positive association exists between rising amounts of oxidants and increasing time of exposure.

[a] Total antioxidant status (TAS); advanced oxidation protein products (AOPPs); ionizing radiation (IR); high absorbed dose (HAD); low absorbed dose (LAD); total antioxidant level(TAL); Glutathione S-Transferase (GST); 8-hydroxy-2' -deoxyguanosine (8-OHdG); 8-oxo-7,8-dihydro-2′-deoxyguanosine (8-oxo-dG); Lipid peroxidation product (LPP); Prooxidant/antioxidant balance (PAB); Chromosome aberrations (CA).

3.3.3.3. Protein oxidative damage marker. The results of a study [23] showed that plasma levels of advanced oxidation protein products (AOPPs) in the exposed group were significantly higher in the control group. Based on the results of another study, the AOPP level within control subjects and all radiation-exposed workers revealed no significant differences [41]. Serum protein carbonyl content was significantly elevated in X-ray technicians compared to the control group [40].

3.3.4. Antioxidants

3.3.4.1. Nonenzymatic antioxidants

3.3.4.1.1. Glutathione. The exposed group showed significantly higher levels of total GSH [17,19] and oxidized GSH [17] compared to the non-exposed group. GSH levels (n = 2) in the test subjects were found to be significantly reduced compared to the control group [20,23]. There was an observed trend of increasing GSH concentration with the increase in annual effective dose [35]. Significant increases in the GSH/GSSG ratio [9] and GSH level (n = 2) [19,42] were noted in the exposed group compared to the non-exposed group. The study found that the relationship between the level of GSH and the X-ray exposure duration was not significant [33], and there was no statistically significant difference in the level of GSH (n = 3) between exposed workers and control individuals [13,17,39]. Additionally, the GSH/GSSG ratio (n = 2) within control subjects and all radiation-exposed workers revealed no significant differences [38,39].

3.3.4.1.2. Thiol. Native thiol (n = 2) [25,26] and total thiol (n = 2) [25,40] values were lower in the exposed group than in the control group. Exposed subjects showed higher levels of thiol groups (n = 1) [37]. No significant differences in disulfide (n = 2) [25,26] and total thiol (n = 1) [26] levels were found between the exposed and unexposed groups.

3.3.4.2. Antioxidant enzymes

3.3.4.2.1. SOD. The study results indicated that the level of SOD was significantly lower in workers who had been exposed to low-dose IR for more than 20 years compared to the controls [6,33,44]. Specifically, SOD levels were lower in workers exposed to interventional radiology-cardiology and nuclear medicine units [9]. The activity of CuZn-SOD in erythrocytes of exposed subjects was also significantly lower than that in unexposed subjects [42]. On the other hand, the activities of CuZn-SOD [5,13,27,28], Mn-SOD [13], and SOD [13,17,39,41] observed in the IR-exposed group were higher than those in the controls. However, Ec-SOD levels within all radiation-exposed workers and control subjects revealed no significant differences [38]. Additionally, there was no significant difference between the exposed and unexposed groups in terms of the seminal plasma SOD level [19].

3.3.4.2.2. Catalase (CAT). The activity of CAT was significantly increased (n = 3) in the exposed group compared to the controls [4,5,41]. The CAT activities in the occupationally exposed group decreased (n = 4) significantly when compared to the control group [15,27,28,44]. There were no statistically significant differences (n = 3) in CAT activity between exposed workers and control individuals [18,39,42].

3.3.4.2.3. Glutathione peroxidase (GPx). There were no statistically significant differences (n = 1) in GPx activity between exposed subjects and control individuals [41]. The Se-GPx activities observed in the exposed group were significantly higher (n = 2) than those in the control group [27,28]. A significant decrease (n = 1) in GPx activity in the test group compared to the control group was observed [44].

3.3.4.2.4. Glutathione S-transferase (GST). The results revealed that the GST activity was significantly reduced in the test group compared to the control group [15].

3.3.4.3. Total antioxidants (TAC). TAC was significantly lower (n = 3) in radiation workers than in controls [9,10,22]. TAC was significantly higher (n = 5) in the exposed participants than in the nonexposed participants [7,16,17,19,37]. The results did not show significant differences (n = 2) in serum TAC [36,42].

3.4. Meta-analysis

3.4.1. 8-OHdG

Three studies including 364 people (177 exposed and 187 unexposed people) measured 8-OHdG levels in blood. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 0.59 [−0.92, 2.10], which did not indicate a significant difference between the two groups (Fig. 2 and Fig. S1). The assessments of Begg's test were as follows: [SE of score = 2.944, Z value = 1.02, P value = 0.3082, I^2 = 97.16].

3.4.2. Reduced glutathione

A total of 286 persons (159 exposed and 127 unexposed people) participated in four studies that tested their reduced glutathione values. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 0.51 [−3.47, 4.48], which did not reveal any

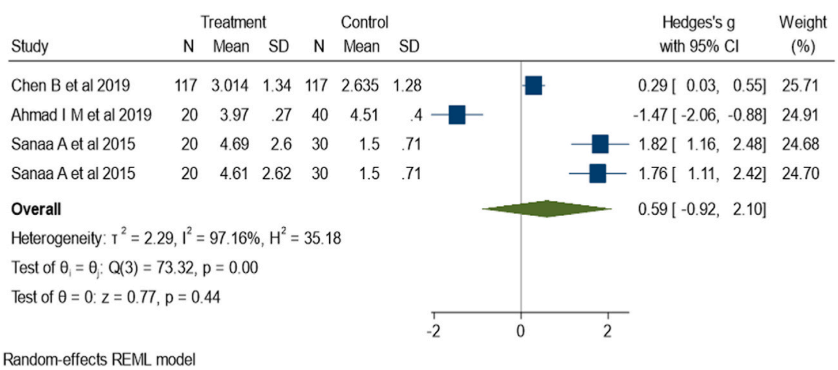

Fig. 2. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting the 8OHDG. The p value was calculated using the Cochrane Q test for heterogeneity.

significant difference between the outcomes for the irradiated and control groups (Fig. 3 and Fig. S2). The assessments of Begg's test were as follows: [SE of score = 2.944, Z value = 0.34, P value = 0.7341, I^2 = 99.22].

3.4.3. CAT

Five studies including 744 subjects (372 exposed and 372 unexposed people) assayed CAT values. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 1.26 [−1.08, 3.61], which indicated no significant difference between the outcomes for the irradiated and control groups (Fig. 4 and Fig. S3). The assessments of Begg's test were as follows: [SE of score = 4.082, Z value = −0.24, P value = 1.0000, I^2 = 99.35].

3.4.4. MDA

All volunteers in the twelve studies were 1343 people (703 exposed and 640 unexposed people) tested for MDA levels. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 1.92 [−1.07, 4.90], which showed no significant difference between the outcomes for the irradiated and control groups (Fig. 5 and Fig. S4). The assessments of Egger's test were as follows: [SE of betal = 4.715, Z value = 3.88, P value = 0.0001, I^2 = 99.79].

3.4.5. SOD

Five studies consisting of 514 individuals (208 exposed and 306 unexposed people) measured SOD values. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 6.66 [−5.03, 18.35], which indicated no significant difference between the two groups (Fig. 6 and Fig. S5). The assessments of Begg's test were as follows: [SE of score = 4.082, Z value = 0.73, P value = 0.4624, I^2 = 99.91].

3.4.6. TAC

589 persons (314 exposed and 275 unexposed people) participated in six studies that tested their TAC values. The overall effect size (hedges' g) with 95 % confidence intervals (CI) was 0.02 [−2.52, 2.56] that did not reveal any significant difference between the outcomes for the irradiated and the control groups (Fig. 7 and Fig. S6). The assessments of Begg's test were as follows: [SE of score = 5.323, Z value = 0.38, P value = 0.7071, I^2 = 99.33].

4. Discussion

Occupational exposure to medical radiation involves continuous and prolonged exposure to low levels of radiation. Ensuring that staff members adhere to radiation safety principles will inevitably reduce their radiation exposure. Protective measures such as using shielding, wearing appropriate clothing, minimizing exposure duration, and increasing distance from radiation sources are crucial [45]. Epidemiological studies have demonstrated that even modest doses of radiation can impact the health of radiation workers [35, 46]. Extended exposure to low levels of radiation is thought to have long-term effects, manifesting years later. Despite the absence of immediate symptoms at the time of exposure, these effects can be significant [31]. Extensive research consistently shows that radiation exposure leads to the creation of free radicals and DNA damage. The body's inability to repair DNA damage increases the risk of developing cancer, particularly in the hematological and immune systems. Cancer risk is influenced by the amount of radiation received, duration of X-ray exposure, and the number of patients handled daily [3,5,31].

It's well-known that even low levels of radiation exposure can have harmful effects that may not be immediately noticeable but can show up years later [31]. Studies have shown that radiation exposure leads to the formation of free radicals and damages DNA, making it more difficult for the body to repair this damage, increasing the risk of cancer. This risk is particularly seen in the immune and blood systems and is influenced by factors like the duration and level of exposure to X-rays, and the number of patients treated daily [3,5,31]. Additionally, radiation exposure can lead to negative health effects like mental health issues and long-term cardiovascular diseases

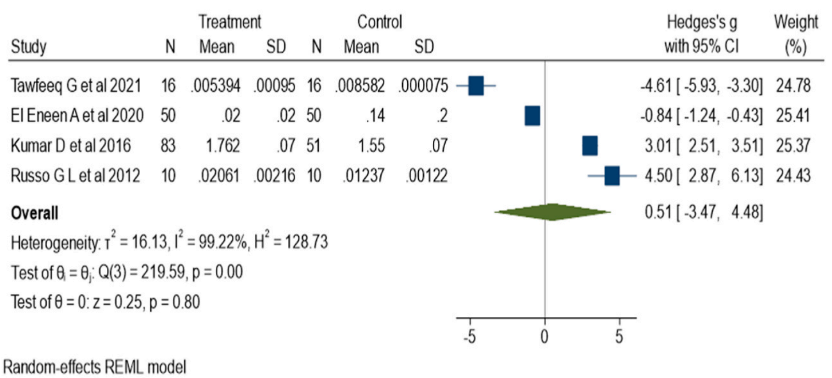

Fig. 3. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting reduced glutathione. The p value was calculated using the Cochrane Q test for heterogeneity.

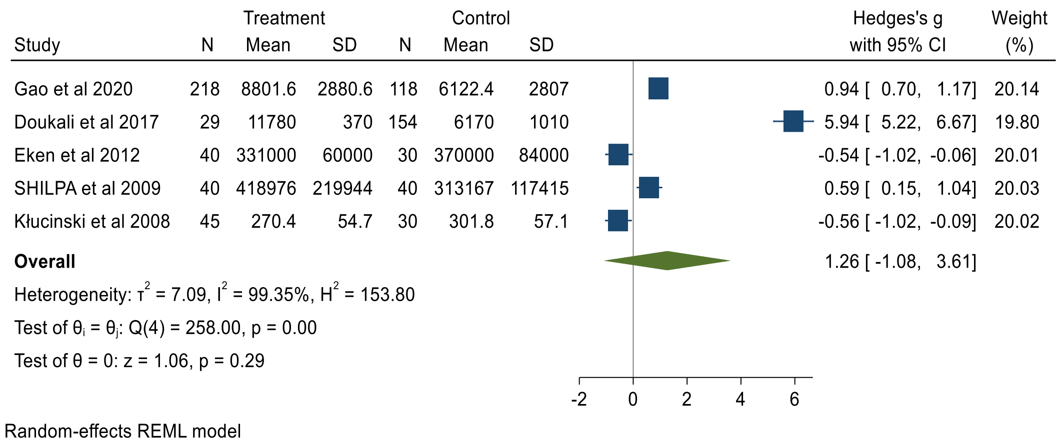

Fig. 4. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting the CAT. The p value was calculated using the Cochrane Q test for heterogeneity.

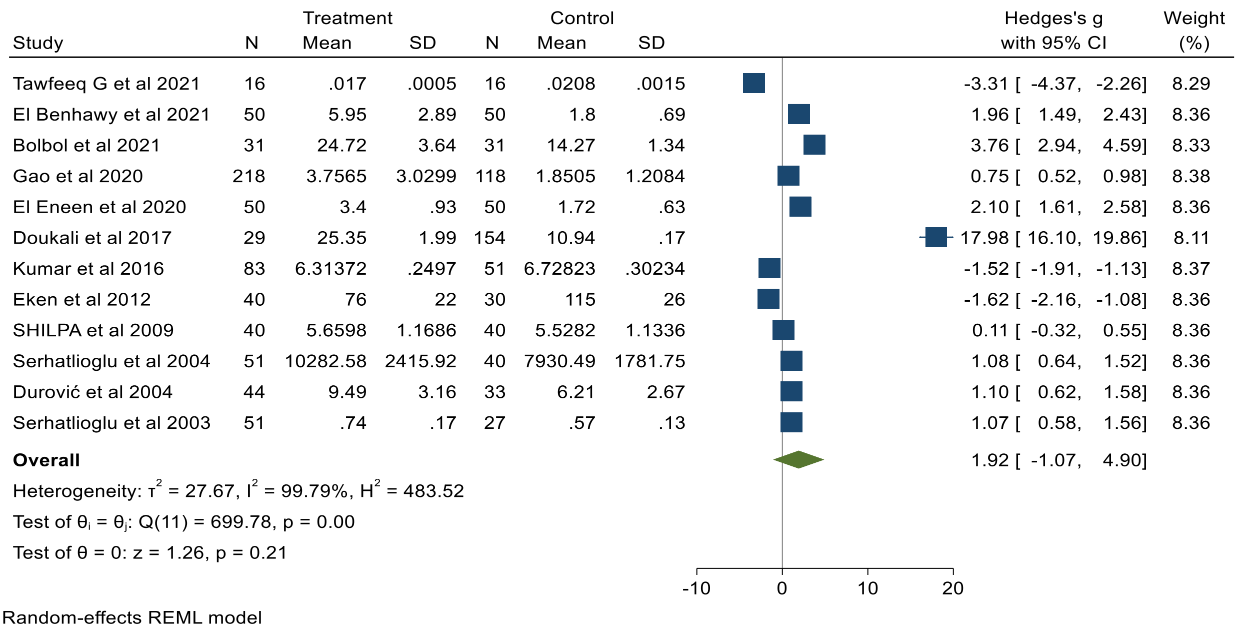

Fig. 5. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting the MDA. The p value was calculated using the Cochrane Q test for heterogeneity.

[35]. Monitoring the blood redox status of healthcare professionals is important to prevent occupational hazards, as oxidative stress can have a range of negative effects. Radiation is known to contribute to the generation of harmful oxygen-free radicals by impacting the body's antioxidant defenses [14]. Several studies have shown changes in biochemical markers linked to prolonged radiation exposure and their connection to the body's ability to fight oxidative stress [15,38].

This systematic review found elevated levels of reactive species like superoxide ($O_2\bullet^-$), NOx, and hydrogen peroxide (H_2O_2) in the exposed groups. This can lead to the formation of peroxynitrite and damage to cellular molecules. However, Russo et al. (42) found no significant differences in the levels of ROS. Additionally, these reactive species play crucial roles in cancer cell invasion and signaling. They can regulate gene activity and promote the production of cytokines, indicating a potential connection between inflammation and carcinogenesis [9,11,44]. The body's overall oxidation and antioxidant capacity are measured using TOS and TAS. The Oxidative Stress Index (OSI) calculates the ratio of TAS to total TOS for a more precise measure of oxidative stress. Ionizing radiation can either stimulate or suppress the immune system, while the impact of infrared exposure depends on the specific cytokine profile and immune system response [47]. Antioxidant levels vary based on factors such as radiation exposure, intake of antioxidants, and protective measures [5]. TAS levels decrease with higher radiation doses due to increased antioxidant consumption. However, prolonged low-level radiation exposure can increase TAS levels by further stimulating antioxidant systems [9,10].

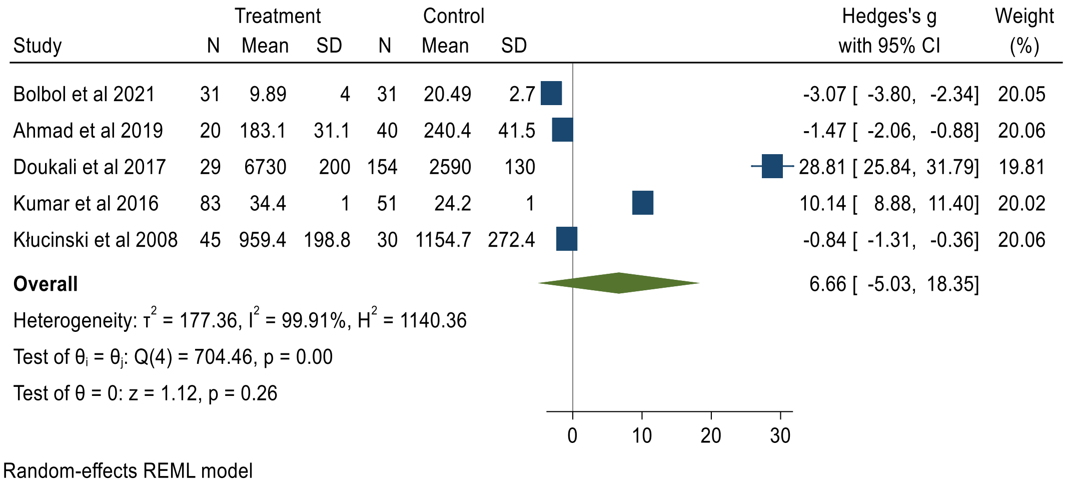

Fig. 6. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting the SOD. The p value was calculated using the Cochrane Q test for heterogeneity.

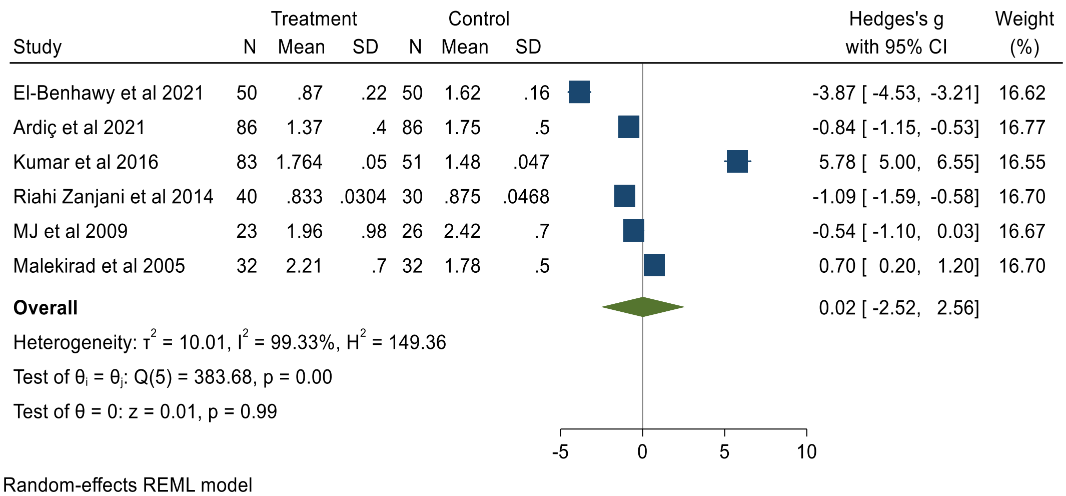

Fig. 7. The forest plot of Hedges' *g* (vertical markers) with its precision (gray square) and 95 % confidence interval (horizontal line) of primary studies reporting the TAC. The p value was calculated using the Cochrane Q test for heterogeneity.

Based on the results of this systematic review and meta-analysis, an increase in the level of metabolic oxidation products was observed in the exposed groups compared to the control group, although in most cases this increase was not significant, because lipid peroxidation in biological systems can be affected by external factors such as smoking, air pollution and UV light as well as internally produced free radicals from enzyme systems and ionizing radiation. Double bonds in lipids containing unsaturated fatty acids increase cell membrane fluidity, impacting its functions. Free radical-induced chain oxidation easily oxidizes polyunsaturated fatty acids and their esters, leading to the formation of reactive lipid hydroperoxides and secondary carbonyl compounds [8]. Guanine is highly susceptible to oxidation due to its low redox potential, leading to the formation of molecules that can cause DNA replication errors. 8-Oxo-7,8-dihydroguanine (8-oxoG) is a common form of oxidative damage to DNA with significant biological consequences [48]. Proteins, due to their high concentrations and rapid reactivity with oxidants, are primary targets for reactive species. The aromatic side chains of proteins are highly susceptible to oxidation and can serve as sensitive indicators of protein oxidation [49].

GSH-Pxs protects the cell membrane from lipid peroxidation. It interacts with proapoptotic and antiapoptotic signaling pathways and controls transcription factors. Moderate oxidative stress can activate natural antioxidant defense mechanisms and increase glutathione levels [6,8,9]. Elevated GSH levels protect cells against genetic alterations. Exposure to low ionizing radiation levels can generate reactive oxygen species and alter antioxidant enzyme function. Assessing oxidative stress levels using indicators such as MDA activity and CAT levels is crucial for evaluating radiation exposure and promoting health [3].

According to the results obtained from the studies in this systematic review, considerable changes in blood oxidative stress biomarkers were reported with exposure to low-dose ionizing radiation in radiation workers of hospital departments. Moreover, the overall effect size of MDA was significantly higher than that of the control group. However, based on the meta-analysis findings of this study, the effect size did not show any notably difference between the two groups for other parameters including 8-OHdG, glutathione depletion, CAT, SOD, and TAC. The increased production of MDA after exposure to radiation can be caused by either a direct effect or a lack of antioxidant defense. This can lead to damage to cell membranes through lipid peroxidation, disrupting cell processes and signaling. Measuring the level of lipid peroxidation can be a quick and cost-effective way to assess radiation exposure in hospital radiation workers, before conducting more extensive studies [12,14,37]. After exposure to ^{56}Fe radiation compared to γ radiation and control groups, there was a significant decrease in the activity of SOD and CAT in intestinal epithelial cells one year later. This suggests that continuous exposure to low-level radiation can reduce the functioning of antioxidant enzymes [50]. Following exposure to radiation, there is a rapid release of reactive species and a sustained increase in ROS levels, leading to prolonged damage to cells, including DNA [15]. People affected by the Chernobyl accident and experiencing postradiation syndrome showed a decrease in the activity of SOD and CAT, indicating an overwhelmed antioxidant system due to increased oxidative stress [44]. The level of 8-OHdG, a marker for DNA damage, can be used to assess injury following exposure to ionizing radiation. Studies have shown elevated levels of 8-OHdG in individuals exposed to radiation, so these changes were evident in the findings of our systematic review. Pilots exposed to cosmic radiation also exhibited an increase in 8-OHdG levels [24,34,51]. It's been suggested that the oxidative degradation of guanine may be the primary cause of telomere fragility and chromosomal abnormalities in individuals occupationally exposed to ionizing radiation [12,24].

5. Limitations and strengths

Limitations of our study include the following: Not all studies published in non-English languages could be included in this review. Few studies have reported the dose received, history of radiation exposure, consumption of antioxidants, and use of shields, so subgroup analysis was impossible due to the wide variation in reported quantities. On the other hand, this research contains strengths for its audience, which can be mentioned in the following, because scientific literature plays a crucial role in influencing political decisions. Our research findings can empower researchers, clinicians, policymakers, and funding agencies to expedite scientific breakthroughs and formulate evidence-based strategies to prevent future injuries to hospital employees in radiology departments. Accurately measuring human exposure to harmful ionizing radiation during hospital work is paramount. It is essential to evaluate the risk of cancer and identify diseases resulting from prolonged exposure to ionizing radiation in hospital employees. Furthermore, designing and implementing long-term cohort studies for employees exposed to ionizing radiation would be instrumental in providing essential support to this group in the future.

6. Conclusion

The impact of radiation exposure on blood oxidative stress levels varied among hospital radiation workers. Our systematic review findings demonstrated a noticeable link between blood oxidative stress markers, length of employment, working in different imaging departments, the number of patients seen daily, and personal effective dose. The results of the review indicated a significant difference in blood oxidative stress markers when exposed to low-dose ionizing radiation among medical radiation workers. Additionally, the overall effect size of MDA was significantly higher than that of the control group. However, there was no significant difference between the two groups for other parameters including 8-OHdG, reduced glutathione, CAT, SOD, and TAC.

CRediT authorship contribution statement

Borhan Mansouri: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Aida Moradi:** Writing – original draft, Formal analysis, Data curation. **Fakhredin Saba:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Data curation, Conceptualization.

Ethics approval and consent to participate

This study was approved by the Research and Ethics Committee of Kermanshah University of Medical Sciences (Ethics code: IR.KUMS.REC.1402.111), and relevant descriptions were provided concerning the aims of the research.

Consent for publication

Not applicable.

Data availability statement

No additional data was used for the research described in the article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39989.

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