Environmental Science and Pollution Research (2023) 30:35757–35768
https://doi.org/10.1007/s11356-022-24652-8

RESEARCH ARTICLE

Exposure to ionizing radiations and changes in blood cells and interleukin-6 in radiation workers

Farshad Bahrami Asl[1] · **Mahdi Islami-seginsara**[1] · **Mohammad Ebrahimi Kalan**[2,3] · **Rasoul Hemmatjo**[4] · **Mousa Hesam**[5] · **Vahid Shafiei-Irannejad**[6]

Received: 4 June 2022 / Accepted: 5 December 2022 / Published online: 20 December 2022

Abstract

Long-term exposure to ionizing radiation (IR) can cause dire health consequences even less than the dose limits. Previous biomonitoring studies have focused more on complete blood counts (CBCs), with non-coherent results. In this study, we aimed to investigate the association between exposure to IR and cytokine interleukin-6 (IL-6) along with hematological parameters in Tabriz megacity's radiation workers. In this hospital-based study, blood samples were taken from 33 radiation workers (exposed group) and 34 non-radiation workers (control group) in 4 hospitals. Absorbed radiation dose was measured by a personal film badge dosimeter in radiation workers. The studied biomarkers and all of the selected covariates were measured and analyzed using adjusted multiple linear regression models. The exposed doses for all radiation workers were under the dose limits (overall mean = 1.18 mSv/year). However, there was a significant association between exposure to ionizing radiation and IL-6 (49.78 vs 36.17; $t = 2.4$; $p = 0.02$) and eosinophils (0.17 vs 0.14; $t = 2.02$; $p = 0.049$). The difference between the mean of the other biomarkers in radiation workers was not statistically significant compared to the control group. This study demonstrated that long-term exposure to ionizing radiation, even under the dose limits, is related to a significantly increased level of some blood biomarkers (Il-6 and eosinophil) that, in turn, can cause subsequent health effects such as cancer.

Keywords CBC · IL-6 · Ionizing radiation · Radiation workers · Tabriz megacity

Introduction

Radiation, fast-moving energy that is emitted as particles or waves, is in two forms non-ionizing radiation (NIR) and ionizing radiation (IR) (Williams and Fletcher 2010). NIR is low-frequency radiation that disperses energy through heat and

---

Responsible Editor: Mohamed M. Abdel-Daim

✉ Farshad Bahrami Asl
Farshadfba@gmail.com

Mahdi Islami-seginsara
mahdihealth@gmail.com

Mohammad Ebrahimi Kalan
mebra006@fiu.edu

Rasoul Hemmatjo
r.hemmatjo@yahoo.com

Mousa Hesam
mhesam66@gmail.com

Vahid Shafiei-Irannejad
vahid.shafiei@hotmail.com

[1] Department of Environmental Health Engineering, School of Public Health, Urmia University of Medical Sciences, Urmia, Iran

[2] Department of Health Behavior, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

[3] Lineberger Comprehensive Cancer Center, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

[4] Department of Occupational Health, School of Public Health, Urmia University of Medical Sciences, Urmia, Iran

[5] Radiation Health Unit, Department of Environmental Health Engineering, Health Vice-Chancellor, Tabriz University of Medical Sciences, Tabriz, Iran

[6] Cellular and Molecular Research Center, Cellular and Molecular Medicine Institute, Urmia University of Medical Sciences, Urmia, Iran

increased molecular movement such as ultraviolet rays (part of it), visible light, infrared rays, and radio waves. IR, which includes alpha and beta particles and some electromagnetic radiations (e.g., gamma and X-rays), can, directly and indirectly, alter the normal structure of a living cell (Nassef and Kinsara 2017). Nowadays, IR and radioactive materials have expanded significantly and have found useful applications in various fields, including medicine, industry, agriculture, and research (Nassef and Kinsara 2017). Medical applications of IR, such as imaging techniques, play an essential role in the early diagnosis of diseases (e.g., cancers), planning and staging of treatment, and patient monitoring (Baker 1990).

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has named X-rays as the most widely used radiation in medicine (UNSCEAR-Annex 2008). In 2008 alone, more than 3,600 million X-ray examinations, 37 million nuclear medicine procedures, and 7.5 million radiotherapy treatments have reported worldwide (Buls 2016), which raised concerns about the potential risk of IR to radiation workers in the related departments (Ahmad et al. 2019). As one of the most widely used radiations in medical science, X-rays can penetrate living tissues and lead to abnormal cell function or death (Baskar et al. 2014; Shi and Tashiro 2018). Therefore, due to its medical side effects, the United States National Cancer Institute (USNCI) has classified these rays as human carcinogens (Zahm and Devesa 1995; Zargan et al. 2016). Exposure to IR can be defined and surveyed as internal and external exposures (Misra et al. 2015). Internal exposure is the entry of radiation into the body caused by inhalation, ingestion, or entry of a radionuclide into the bloodstream (by injection, through open wounds, etc.). Internal radiation can be stopped by spontaneously removing radionuclides from the body or under various treatments' influence (Ionizing radiation 2016). In external exposure, radioactive material does not enter the body. In other words, the radiation source is out of the body, and depending on the type of radiation, different protection methods can be used (Salvato et al. 2003). Studies have shown that exposure to high doses of IR can cause various cancers. However, exposure to low doses also can have adverse health effects (Piotrowski et al. 2017; Suzuki and Yamashita 2012). Therefore, different dose limits have been defined for exposure to radiation, which varies depending on different conditions such as exposure type (public or occupational) and exposed body organ. The dose limits for radiation exposures are presented in Table 1 (Oztas et al. 2012).

Table 1 Dose limits for occupationally exposed workers and the public (Oztas et al. 2012)

Type of limit	Occupational	Public
Stochastic limits		
Effective dose	20 mSv per year, averaged over defined periods of 5 years	1 mSv in a year
Deterministic limits, annual equivalent dose in		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	-

mSv, millisievert; 1 Sv is equal to 100 rontgen equivalent man (rem). The roentgen equivalent man denotes a CGS* unit of equivalent dose, effective dose, and committed dose, which are measures of the health impact of low levels of ionizing radiation on the human body

*CGS is the abbreviation of unit system. In the CGS system, fundamental units are centimeter, gram, and second

Immune cells, including lymphocytes, are the most sensitive cells to moderate and high levels of radiation (Schaue and McBride 2012), with the potential risk of mutagenicity and carcinogenicity from exposure to IR has been reported (Hayata 2005; Hei et al. 2005) and discussed in many studies (Mavragani et al. 2017). The radiation workers in various diagnostic and therapeutic settings (e.g., hospitals and clinics) are exposed to low-dose radiation for a long time despite the use of personal protective equipment and employing the instructions (Cheon et al. 2018; Gaskin et al. 2014). The use of IR is common in various wards of a hospital, including radiography and nuclear medicine (Dorfman et al. 2011). Hence, clinicians, nurses, technicians in radiology departments, and paramedics are people who can be exposed to IR in hospitals (Szarmach et al. 2015). Evidence shows that the frequency of chromosomal damage in these individuals, even those exposed to less radiation than dose limits, was higher than normal individuals (Jha and Sharma 1991; Kasuba et al. 2005; Kim et al. 2017; Linet et al. 2012), putting workers at risk of cancers, especially brain cancer (Rajaraman et al. 2016). The mechanism of this health effect is yet to be explored. At the same time, elevated levels of reactive oxygen species (ROS), oxidative DNA damage, and Immunosuppression triggered by exposure to IR are mentioned as possible reasons (Ahmad et al. 2019). Previous studies have shown that exposure to IR in radiation workers, even under the dose limits recommended by International Commission on Radiological Protection, changes the redox of the environment by increasing the amount of ROS, especially superoxide (Ahmad et al. 2016, 2019). In addition, evidence shows that chronic oxidative stress is involved in many pathological conditions such as inflammation, fibrosis, necrosis (Citrin et al. 2012; Shi and Tashiro 2018), DNA damage, and cancers (Jacob et al. 2009; Zakeri and Hirobe 2010; Zielinski et al. 2009). Understanding the potential health effects of exposure to IR, especially among radiation workers, is crucial to better tailor targeted preventive interviews to reduce harmful exposure to IR. Therefore, in this study, we aimed to investigate the relationship between exposure to IR and changes in interleukin-6 (IL-6) and complete blood count (CBCs) (i.e., white blood cells (WBC), neutrophils, lymphocyte, monocyte, eosinophil, basophil, red blood cells (RBC), hemoglobin

(HGB), hematocrit (HCT), mean cell volume (MCV), mean corpuscular hemoglobin (MCH), mean cell hemoglobin concentration (MCHC), cellular hemoglobin concentration mean (CHCM), red blood cell distribution width (RDW), platelet (PLT), mean platelet volume (MPV)) in radiation workers of different related hospital wards (diagnostic and therapeutic) in Tabriz, northwest of Iran. The reference ranges of the studied biomarkers are shown in Table 2 (43).

Methods

Study design

A cross-sectional study was conducted to explore the effects of long-term exposure to IR in radiation workers in Tabriz megacity hospitals from May 1, 2016 to May 1, 2021. Two study groups were selected as exposed (radiation workers) and unexposed (control) to IR. Despite previous studies that have shown no significant effects of work experience on the level of biomarkers (Tavakkoli et al. 2012; Zargan et al. 2016), radiation workers with work experience of more than 10 years were selected as the exposed group. All study sections took place in a private room in each hospital to ensure the confidentiality of information. A de-identified code also was assigned for each study participant.

Table 2 Reference dose of the studied biomarkers (Samadi et al. 2019, 2020)

Biomarker			Normal range of biomarker	Unit
IL-6	The different ranges were reported, and it can be various depending on the community. Hence, it is preferred to compare with the control group			
CBC	RBC		4.2–6.1	1,000,000/µL
	HGB		12–18	g/dL
	HCT		37–54	%
	MCV		80–99	Femtoliters
	MCH		26.4–32	pg
	MCHC		31–36	g/dL
	CHCM		31–37	g/dL
	RDW		11.5–16	%
	WBC	Adults (> 21 years)	4–11	1000/µL
	Neutrophils	Adults (> 21 years)	1.9–8	1000/µL
	Lymphocytes	Adults (> 21 years)	0.9–5.2	1000/µL
	Monocytes		0.16–1	1000/µL
	Eosinophils		0–0.8	1000/µL
	Basophils		0–0.2	1000/µL
	PLT		130–440	1000/µL
	MPV		6.1–11.1	Femtoliters

Study population

To calculate the sample size for this study, we considered the mean (SD) concentration of the IL-6 as 0.44 pg/mL (0.08) in control and 0.83 pg/mL (0.21) in the exposed group based on previous literature (Ahmad et al. 2019). Power analysis with $\alpha = 0.05$ and $\beta = 0.80$ yielded a sample of 30 participants for each group. To increase the study power, 10% of the sample size was added to the original sample, resulting in 67 participants; $n = 33$ radiation workers and $n = 34$ control group. Stratified random sampling was applied to select the final sample for each group. To reduce selection bias, participants in the control group were selected from the staff of the same hospitals who were not exposed to IR. Work experience of less than 10 years for radiologists, age less than 20 years and more than 60 years, presence of chronic and acute disease for all participants, and pregnancy for females were the exclusion criteria of the present study.

Covariates

The literature review showed that factors such as FBS (Kitsios et al. 2012; Mohammadi et al. 2017; Pradhan et al. 2001; Sarbijani et al. 2016), BMI (Kitsios et al. 2012; Pradhan et al. 2001; Roytblat et al. 2000), smoking (Aldaham et al. 2015; de Maat and Kluft 2002), age (Aldaham et al. 2015), medical supplements and physical activity (Eder et al. 2009) can affect the levels of studied biomarkers. Hence, self-reported demographic characteristics and medical history were assessed including sex (male/female), age (years), body height (cm), body weight (kg), body mass index (BMI; body weight divided by the square of the body height; normal ≤ 24.9, overweight $= 25$ to 29.9, and obese ≥ 30 kg/m^2), diabetes mellitus (DM), physical activity, consumption of alcohol and dietary supplements, smoking status, history of diseases such as thalassemia, hemophilia, and infections and history of taking certain medications. Glucose oxidase kits (PARS AZMUN) were used to assess the FBS and DM (FBS ≥ 126 mg/dL) (Samadi et al. 2019, 2020). Participants who were taking diabetes-related medications were considered diabetic patients. Bodyweight and height were measured using a standard scale and stadiometer (Body Scale BS769), respectively, (Pietrobelli et al. 1998). Participants who presently smoked cigarettes, participants who have smoked 100 cigarettes in life but currently not smoking, and participants who had smoked less than 100 cigarettes in life were defined as current, former, and never status, respectively (Samadi et al. 2019). Physical activity was assessed using the Godin Leisure Exercise Questionnaire (Ahmad et al. 2019).

Absorbed radiation dose estimation

The absorbed dose in radiation workers was measured by a personal film badge (FUMA, Japan). The dosimetry was performed every 2 months and estimated by PARSIAN and SANJESH PARTO MEHR ARSHID companies.

Blood markers

We evaluated selected biomarkers (e.g., IL-6 and CBCs) considering the normal range based on the previous studies (Samadi et al. 2019, 2020). We obtained venous blood samples (by trained nurses) in each study site (i.e., hospital). The separated serum was shipped to a laboratory in a cold box at about 4 °C and was kept at − 80 °C immediately (El-Mikkawy et al. 2020). IL-6 was measured using ELISA (Karmania Pars Gene ELISA kits, Karmania Pars Gene Co, Kerman, Iran) and an automatic analyzer (AWARENESS STAT FAX 2100). CBC was measured by an automatic hematology analyzer (Siemens ADVIA360).

Statistical analyses

Spearman rank correlation was used to examine the correlation between quantitative parameters (age, FBS, BMI, etc.) with dependent variables (CBCs and IL-6). The difference between average exposure dose in various working wards (angiography, radiotherapy, nuclear medicine, radiology, and CT scan) was evaluated by one-way analysis of variance (ANOVA). Independent Student's *t*-test was used to examine the association between dependent variables and demographic characteristics (e.g., age, sex, BMI) and medical history (e.g., DM). The effect of working ward and smoking status on dependent variables was evaluated by ANOVA followed by post hoc Tukey's method. Multiple linear regression models were used to assess the association between exposure to IR and biomarkers after adjusting for confounders. All statistical analyses were performed in the Stata software, version 14 (StataCorp), at a significance level of 0.05.

Results

The mean age of participants was 39.9 (± 1.1) years, with 52% female, and the mean BMI of 26.32 kg/m^2. Of all participants, 91% were non-smokers, 57% had insufficient physical activity, and 96% had lower FBS (< 126 mg/dL). None of the participants consumed alcohol, and 19% of participants reported a history of taking dietary supplements or chronic medical conditions (Table 3).

The average absorbed dose (5 years' periods) of the radiation workers is shown in Table 4. The absorbed dose for all of the radiation workers was lower than the defined dose limits (Table 1). The reference range and descriptive statistics of the studied biomarkers are shown in Table 2 (Samadi et al. 2019) and Table 5, respectively. After adjusting for potential confounders, our regression models show the significant difference in the mean concentration of IL-6 in radiation workers compared to the control group (49.78 vs. 36.17, $p = 0.02$) (Table 6). In the case of CBC, only the significant difference in the mean concentration of eosinophils was observed between the radiation workers compared to their counterparts (0.17 vs. 0.14, $p = 0.049$) (Table 7).

As shown in Table 4, maximum and minimum absorbed radiation dose was related to the radiology, and radiotherapy wards, respectively. The highest mean absorbed dose was related to CT scan and then nuclear medicine wards.

Two-sample *t*-test (results not shown) demonstrated that the level of MCV in radiation workers who had a cold in the past month was lower than the other radiation workers ($p = 0.016$). In the case of medical supplement consumption, in the control group, the level of RBC ($p = 0.008$), HGB ($p = 0.036$), HCT ($p = 0.02$), CHCM ($p = 0.038$), and lymphocytes ($p = 0.044$) in individuals who taking medical supplements is significantly lower than the individuals who do not take medical supplements. However, the opposite of this result is true in the case of neutrophils level ($p = 0.022$). In radiation workers, the MPV level is significantly lower in individuals who do not take medical supplements ($p = 0.01$). Regarding the special drug consumption, RDW, MPV, and neutrophil levels are significantly higher in radiation workers who take special drugs ($p = 0.001$, 0.02, and 0.023, respectively). In the control group, the lymphocyte level is significantly higher in individuals with a history of a specific disease ($p = 0.044$).

According to the results of Spearman rank correlation (results not shown), no significant relationship was observed between FBS and studied biomarkers. Physical activity had a significant negative relationship with MCH only in radiation workers ($r = -0.368$, $p = 0.039$). However, there was a significant negative relationship between BMI and RBC ($r = -0.401$, $p = 0.019$), HCT ($r = -0.403$, $p = 0.018$) and CHCM ($r = -0.412$, $p = 0.015$) in control group and a significant positive relationship with eosinophils ($r = 0.389$, $p = 0.028$) in radiation workers. Doing any regular activity long enough to work up a sweat at work during a typical 7-Day period has a significant negative correlation with CHCM ($r = -0.569$, $p = 0.001$) and MCHC ($r = -0.399$, $p = 0.019$) in control group and a significant

Table 3 Descriptive statistics of the study population ($n=67$)

Characteristic	All participants	Radiation workers	Control group
	Person (percentage) or mean ± SD		
Overall	67 (100)	33 (49)	34 (51)
Sex			
Male	32 (48)	17 (52)	15 (44)
Female	35 (52)	16 (48)	19 (56)
Age (years)	39.89 ± 1.1	39.51 ± 10.47	40.26 ± 7.82
20–29	13 (19)	10 (30)	3 (9)
30–39	18 (27)	4 (12)	14 (41)
40–49	23 (35)	12 (37)	11 (32)
50–59	13 (19)	7 (21)	6 (18)
BMI (kg/m^2)	26.32 ± 3.32	25.45 ± 2.84	27.16 ± 3.57
Normal (≤ 24.9)	21 (31)	14 (42)	7 (21)
Overweight (25 to 29.9)	35 (53)	16 (49)	19 (56)
Obese (≥ 30)	11 (16)	3 (9)	8 (23)
Smoking			
Never	61 (91)	27 (82)	34 (100)
Former	4 (6)	4 (12)	0 (0)
Current	2 (3)	2 (6)	0 (0)
Physical activity (Godin Leisure-Time Exercise)			
Active	15 (22)	7 (21)	8 (24)
Moderately active	14 (21)	6 (18)	8 (24)
Insufficiently active	38 (57)	20 (61)	18 (52)
Doing any regular activity long enough to work up a sweat during a typical 7-day period			
Never	24 (36)	14 (42)	10 (29)
Sometimes	35 (52)	16 (49)	19 (56)
Often	8 (12)	3 (9)	5 (15)
FBS (mg/dL)	85.16 ± 15.29	86.64 ± 15.38	83.73 ± 15.28
˂ 126	64 (96)	31 (94)	33 (97)
≥ 126	3 (4)	2 (6)	1 (3)
Alcohol consumption			
No	67 (100)	33 (100)	34 (100)
Yes	0 (0)	0 (0)	0 (0)
Medical supplement consumption[1]			
No	54 (81)	27 (82)	27 (79)
Yes	13 (19)	6 (18)	7 (21)
Special drug consumption[2]			
No	59 (88)	29 (88)	30 (88)
Yes	8 (12)	4 (12)	4 (12)
Catching a cold last month			
No	58 (87)	29 (88)	29 (85)
Yes	9 (13)	4 (12)	5 (15)
History of thalassemia or hemophilia			
No	67 (100)	33 (100)	34 (100)
Yes	0 (0)	0 (0)	0 (0)
History of other specific diseases			
No	61 (79)	29 (88)	32 (94)
Yes	6 (21)	4 (12)	2 (6)
Work experience (years)			
10–15	-	23 (70)	-
15–20	-	10 (30)	-

[1] Medical supplements including various types of multivitamins

[2] Special drugs including levothyroxine, metformin, and atenolol

Table 4 Average exposure dose (5 years' periods) of radiation workers depending on working place

Radiation workers' in	Number of studied radiation workers	The average absorbed dose (mSv/year)		
	Person (percentage)	Mean ± SD	Min	Max
Overall	33 (100)	1.18 ± 2.91	0	13.33
Angiography ward	6 (18)	1.14 ± 2.68	0	6.62
Radiotherapy ward	5 (15)	0.04 ± 0	0.04	0.04
Nuclear medicine ward	4 (12)	1.54 ± 1.1	0.48	3.06
Radiology ward	13 (39)	1.06 ± 3.69	0	13.33
CT scan ward	5 (15)	1.98 ± 3.86	0.04	8.86

positive correlation with MCH ($r=0.403$, $p=0.022$) in radiation workers. In control group, age had a significant negative relationship with MCHC ($r=-0.341$, $p=0.048$) and a significant positive relationship with Neutrophil ($r=0.395$, $p=0.02$) and leukocytes ($r=0.345$, $p=0.045$).

ANOVA followed by Tukey's method demonstrated that, the level of RBC ($p=0.027$), HGB ($p=0.019$), HCT ($p=0.018$), and CHCM ($p=0.037$) in former smokers is significantly higher than non-smokers. In addition, the results showed that the level of HCT ($p=0.026$) and MPV ($p=0.045$) in current smokers was significantly higher than in non-smokers. However, the level of MPV ($p=0.025$) is higher in current smokers than in former smokers.

Discussion

In this study, the mean serum levels of IL-6 and eosinophils in radiation workers were higher than the control group. We also found that the absorbed radiation dose for all of the radiation workers was lower than the defined dose limits, and the mean concentrations of all studied biomarkers fell within the standard ranges. Our findings, in general, show that the long-term exposure to IR, even lower than defined threshold limitations, can alter some of the biomarkers, namely IL-6 and eosinophils.

The normal range of IL-6 serum levels varies depending on the community. Therefore, it is preferable to use the control group's mean as a reference range. This range in our control group was (~ 36) but was markedly higher in radiation workers (~ 48). Although IL-6 has been identified as one of the protein biomarkers associated with radiation injuries in total and partial-body exposure (Blakely et al. 2014; Ossetrova et al. 2014a, b; Redon et al. 2011), elevated levels of IL-6 have been identified in animal and human studies as a major mediator of potential health outcomes (Kulkarni et al. 2013; Singh et al. 2010, 2011, 2012a, b, c, 2014). For example, Citrin et al. (2012) reported a dose–response association between the neck and head radiotherapy and expression of IL-6 and some of the other cytokines. This is worrisome especially in the current global crisis. For example, higher levels of IL-6 are associated with increased risk of mortality from several diseases such as COVID-19.

Table 5 Descriptive statistics of the studied biomarkers

Biomarkers			All participants Mean ± SD	Radiation workers	Control group	Unit	*p*-value
IL-6			42.88 ± 30.25	49.78 ± 22.68	36.17 ± 35.18	Pg/mL	**0.020**
CBC	RBC		5.02 ± 0.53	5.06 ± .56	4.98 ± 0.5	1000000/µL	1.000
		HGB	14.41 ± 1.62	14.61 ± 1.77	14.42 ± 1.46	g/dL	0.717
		HCT	44.26 ± 4.65	45.02 ± 5.16	43.52 ± 4.03	%	0.408
		MCV	88.27 ± 4.29	88.99 ± 4.17	87.57 ± 4.36	Femtoliters	0.296
		MCH	27.78 ± 1.45	28.95 ± 1.27	28.61 ± 1.61	pg	0.435
		MCHC	32.56 ± 0.88	32.45 ± 1.01	32.67 ± 0.73	g/dL	0.202
		CHCM	32.89 ± 0.97	33.07 ± 1.04	32.73 ± 0.88	g/dL	0.845
		RDW	13.88 ± 1.02	13.65 ± 0.92	14.11 ± 1.07	%	0.118
	WBC		7.19 ± 1.65	7.44 ± 1.79	6.96 ± 1.5	1000/µL	0.114
		Neutrophils	4.23 ± 1.23	4.3 ± 1.41	4.15 ± 1.04	1000/µL	0.148
		Lymphocytes	2.17 ± 0.68	2.3 ± 0.68	2.03 ± 0.66	1000/µL	0.389
		Monocytes	0.49 ± 0.13	0.5 ± 0.13	0.47 ± 0.14	1000/µL	0.343
		Eosinophils	0.16 ± 0.11	0.17 ± 0.09	0.14 ± 0.11	1000/µL	**0.049**
		Basophils	0.04 ± 0.02	0.05 ± 0.02	0.04 ± 0.02	1000/µL	0.986
	PLT		245.3 ± 57.91	233.36 ± 62.45	256.88 ± 51.44	1000/µL	0.581
		MPV	7.38 ± 0.87	7.3 ± 0.8	7.47 ± 0.94	Femtoliters	0.455

Bold numbers indicate the biomarkers that are affected by exposure to ionizing radiation

Table 6 The association between IL-6 levels and selected covariates in radiation workers using multiple linear regressions

Adjusted covariates	Coefficient	95% conf. interval		*p*-value
Studied groups				
Control group	Reference			
Radiation workers	1.15	0.19	2.11	**0.02**
FBS (mg/dL)				
˂ 126	Reference			
≥ 126	−1.34	−3.56	0.87	0.228
Sex				
Male	Reference			
Female	−0.3	−1.3	0.7	0.547
Age (years)				
20–29	Reference			
30–39	0.45	−0.95	1.85	0.518
40–49	0.36	−0.96	1.68	0.590
50–59	0.39	−1.23	2.02	0.627
BMI (kg/m^2)				
Normal (≤ 24.9)	Reference			
Overweight (25 to 29.9)	−0.01	−1.05	1.02	0.979
Obese (≥ 30)	−0.18	−1.61	1.25	0.798
Medical supplement consumption				
No	Reference			
Yes	0.32	−0.91	1.56	0.601
Smoking				
Never	Reference			
Former	0.82	−1.14	2.78	0.403
Current	0.75	−2.63	3.86	0.630
Caught cold last month				
No	Reference			
Yes	0.05	−1.24	1.34	0.937
History of specific diseases				
No	Reference			
Yes	0.35	−1.92	2.62	0.756
Special drug consumption				
No	Reference			
Yes	0.97	−0.72	2.67	0.255
Physical activity (Godin Leisure-Time Exercise)				
Active	Reference			
Moderately active	0.66	−0.74	2.07	0.348
Insufficiently active	0.59	−0.57	1.74	0.311
Doing any regular activity long enough to work up a sweat during a typical 7-day period				
Never	Reference			
Sometimes	0.16	−0.83	1.16	0.741
Often	1.28	−0.33	2.89	0.118

Bold numbers indicate the biomarkers that are affected by exposure to ionizing radiation

Table 7 The association between eosinophil levels and selected covariates in radiation workers using multiple linear regressions

Adjusted covariates	Coefficient	95% conf. interval		*p*-value
Studied groups				
Control group	Reference			
Radiation workers	0.48	.002	0.96	**0.049**
FBS (mg/dL)				
˂ 126	Reference			
≥ 126	−0.65	−1.75	0.44	0.237
Sex				
Male	Reference			
Female	−0.23	−0.72	0.27	0.363
Age (years)				
20–29	Reference			
30–39	0.31	−0.38	1.00	0.373
40–49	0.16	−0.50	0.82	0.626
50–59	−0.11	−0.92	0.70	0.778
BMI (kg/m^2)				
Normal (≤ 24.9)	Reference			
Overweight (25 to 29.9)	0.21	−0.30	0.72	0.417
Obese (≥ 30)	−0.03	−0.74	0.68	0.929
Medical supplement consumption				
No	Reference			
Yes	−0.27	−0.89	0.34	0.372
Smoking				
Never	Reference			
Former	−0.14	−1.11	0.84	0.778
Current	0.006	−1.54	1.55	0.994
Caught cold last month				
No	Reference			
Yes	−0.27	−0.91	0.38	0.408
History of specific diseases				
No	Reference			
Yes	0.45	−0.68	1.58	0.425
Special drug consumption				
No	Reference			
Yes	−0.17	−1.01	0.67	0.683
Physical activity (Godin Leisure-Time Exercise)				
Active	Reference			
Moderately active	0.03	−0.67	0.73	0.929
Insufficiently active	0.07	−0.50	0.65	0.795
Doing any regular activity long enough to work up a sweat during a typical 7-day period				
Never	Reference			
Sometimes	−0.07	−0.56	0.43	0.786
Often	0.39	−0.42	1.19	0.338

In COVID-19 patients (especially healthcare providers who are at greater risk), higher IL-6 levels increase the chance of mechanical ventilation requirements and can lead to severe SARS-CoV-2 induced pneumonia (Guirao et al. 2020).

Exposure to IR can change the numbers and functions of immune system cells and cause an inflammatory response, which activates various pro-survival pathways and factors such as nuclear factor kappa B (NF-kB) and members of signal transducers and activators of transcription (STATs) (Criswell et al. 2003; Dent et al. 2003; Meeren et al. 1997; Najafi et al. 2017a). By regulating the expression of pro-inflammatory cytokines such as IL-6, NF-kB plays an important role in inflammatory and immune responses (Calò et al. 2003; Yu et al. 2009). Moreover, exposure to IR can cause the expression of many other growth factors and cytokines such as GM-CSF, interferon-gamma (IFN-γ), tumor necrosis factor (TNF-α), transforming growth factor-beta (TGF-β), IL-1β, IL-1α, IL-33, IL-18, IL-12, IL-10, IL-4, and IL-5 (Di Maggio et al. 2015; Najafi et al. 2017b). IL-6, along with other extracellular ligands such as PDGF and EGF, can activate STATs, which can stop or develop the tumor (Calò et al. 2003; Yu et al. 2009). This pathway's protective or adverse outcome depends on the pro-inflammatory and anti-inflammatory cytokines balances (Sun et al. 2013). For example, STAT3 as an oncogene can promote cell proliferation (tumor developer), while STAT1 stimulates and enhances anti-proliferative, inflammation, and immunity responses (tumor stopper) (Calò et al. 2003; Shen et al. 2001). The radiation resistance in increased levels of IL-6 and radiation sensitivity in decreased levels of IL-6 have been reported previously in prostate cancer cells (Wu et al. 2013). Hence, it is crucial to consistently monitor the levels of IL-6 among radiation workers to avoid dire health consequences.

Although our findings yielded significant results only for one CBC parameter, namely eosinophils in radiation workers compared to the control group. However, contrary to this result, some previous studies found that radiation exposure does not significantly affect the number of neutrophils (Buescher and Gallin 1984; Rees et al. 2004; Schubauer-Berigan and Wenzl 2001). They attributed this result to the relative resistance of phagocytes to irradiation. In line with our findings, other studies have reported no association between exposure to low dose radiation and WBC (Forslund et al. 1985; Heydarheydari et al. 2012; Meo 2004; Salek Moghaddam et al. 2004; Shafiee et al. 2016a; Zargan et al. 2016), PLT (Heydarheydari et al. 2012, 2016; Sayed et al. 2011; Shafiee et al. 2016a; Tavakkoli et al. 2012; Zargan et al. 2016), RBC (DavudianTalab et al. 2018; Meo 2004; Mezhoud et al. 2014; Shafiee et al. 2016a), MCH (Mezhoud et al. 2014; Shafiee et al. 2016a), MCHC (Shafiee et al. 2016a), HCT (Hauck et al. 2011; Mezhoud et al. 2014; Shafiee et al. 2016a), HGB (Hauck et al. 2011; Mezhoud et al. 2014), and MCV levels (Mezhoud et al. 2014). Nevertheless, statistically significant decreases in WBC (Davoudi et al. 2012; Mezhoud et al. 2014; Shahid et al. 2015a; Tavakkoli et al. 2012), neutrophil (Shahid et al. 2015a; Taqi et al. 2018), monocytes (Taqi et al. 2018), basophile (Taqi et al. 2018) lymphocytes (Sabagh and Chaparian 2019), PLT (Dainiak 2002; Davoudi et al. 2012; Faraj and Mohammed 2018; Meo 2004; Mezhoud et al. 2014; Sabagh and Chaparian 2019; Shafiee et al. 2016b; Shahid et al. 2015a; Taqi et al. 2018), RBC (Abdolmaleki et al. 2012; Heydarheydari et al. 2016), HGB (Abdolmaleki et al. 2012; Heydarheydari et al. 2016; Shahid et al. 2015a), MCV (Abdolmaleki et al. 2012; Heydarheydari et al. 2016; Taqi et al. 2018), RDW (Taqi et al. 2018), HCT (Shahid et al. 2015a), MCH (Shahid et al. 2015a, 2014), and MCHC levels (Sabagh and Chaparian 2019; Shahid et al. 2015a) were reported in radiation workers compared with the control group. Also, the result of some studies yielded a significantly increased level of WBC (Nureddin and Alatta 2016), lymphocytes (Shahid et al. 2015a; Taqi et al. 2018), PLT (Nureddin and Alatta 2016; Sayed et al. 2011), RBC (Shahid et al. 2015a; Taqi et al. 2018), MCV (Abdolmaleki et al. 2012), HGB (Shahid et al. 2015a; Taqi et al. 2018), and HCT (Sabagh and Chaparian 2019; Shahid et al. 2015a; Taqi et al. 2018) in response to low-dose radiation. Several factors could explain these discrepancies and commonalities between previous literature and our findings, including study design, study sites, sample of study, characteristics of the participants (whether the radiation workers or control group), time of blood sampling, and other covariates (e.g., time and duration of exposure), and more importantly we cannot preclude the reporting bias that may cause some differences between findings. Future large multicenter longitudinal studies are warranted to investigate these differences in various populations deeply.

As a result of exposure to various hospital infections, hospital staff has a stronger immune system than normal individuals (Faraj 2021). However, studies that have reported a positive association between CBC counts and radiation exposure identified the hematopoietic acute radiation syndrome, an acute toxic syndrome that was reported as a result of total body exposure to IR dose between 0.7 and 10 Gy, as a possible reason (Billings et al. 2014; Ma et al. 2010; Shahid et al. 2014, 2015b). In contrast, other studies explain the adaptive response as a reason why exposure to a low dose of IR does not affect CBC counts. In this phenomenon, body organs that are exposed long-term to low dose radiations have sufficient time to restore the damaged cells and increase the levels of cell cytoprotective genes. Thus, in subsequent exposures, the body becomes resistant to IR (Feinendegen et al. 2004; Kadhim et al. 2004; Liu et al. 2006; Salek Moghaddam et al. 2004; Schimmöller et al. 2014; Tucker 2008).

Our adjusted regression model showed that WBC, PLT, and monocytes in individuals with higher levels of FBS (≥ 126 mg/dL) were significantly lower than the individuals with lower FBS (i.e., < 126 mg/dL). CHCM and HDW significantly decrease with increasing weight, but this difference is only statistically significant in participants with overweight (BMI = 25 to 29.9 kg/m^2) compared to participants with BMI within normal range (BMI ≤ 24.9 kg/m^2). MPV in middle-aged participants (30–49 years) was significantly higher than the younger counterparts (20–29 years old). Neutrophils increase with increasing age, and this difference was statistically significant among participants aged 30–59 years compared to 20–29 years. This was expected since associations between age and CBC parameters were reported in the literature (Burton et al. 1983; Fujiwara et al. 1986; Tuschl et al. 1990). For instance, decreased number of WBC has been reported with increasing age (DavudianTalab et al. 2018). Prevention programs should consider demographic characteristics to achieve effective outcomes in the targeted population, especially radiation workers.

Two-sample *t*-test (results not shown) demonstrated that the level of RBC ($p = 0.0$ for both radiation workers and control groups), HGB ($p = 0.0$ for both radiation workers and control groups), HCT ($p = 0.0$ for both radiation workers and control groups), and CHCM ($p = 0.003$ for radiation workers and $p = 0.006$ for control group) were higher in males than females. However, the PLT level in female radiation workers was higher than the male radiation workers ($p = 0.002$). (DavudianTalab et al. 2018) reported no significant difference for CBC between the radiation worker and control group by gender. However, similar to the results of the current study, the level of RBC, HGB, HCT, MCHC, and lymphocytes was reported significantly higher in males, and PLT was reported significantly higher in female radiation workers by (Sabagh and Chaparian 2019).

Our findings were in line with previous research showing that the increased levels of RBC (Anandha Lakshmi et al. 2014), HGB (Anandha Lakshmi et al. 2014; Malenica et al. 2017; Whitehead et al. 1995), HCT (Anandha Lakshmi et al. 2014; Whitehead et al. 1995), and CHCM (Malenica et al. 2017) were higher in current smokers than non-smokers. To minimize radiation exposure, it is recommended that radiation workers be trained in the use of personal protection instructions. In addition, using dietary supplements (including antioxidants such as vitamins E, C, B6) potentially can protect the risks on immune systems of radiation workers (Guan et al. 2006). The SARS-CoV-2 pandemic, lack of access to all hospitals, and poor cooperation of radiologists were the limitations of the present study. In addition, it is recommended that under normal conditions, the number of participants in the control or non-exposed group should be twice the number of the exposed group, and the environmental exposure to radiation (including; external radiation exposures such as sunlight and climate-related radiations, and internal radiation exposures such as contaminated water, foods, and respirable air) should also be measured.

Conclusion

This study revealed that hazardous exposure to IR after adjusting for significant covariates was significantly associated with increased IL-6 and eosinophils in radiation workers compared to the non-exposed control group in several hospitals in Iran. We found that the absorbed dose in all radiation workers was lower than the dose limits. Hence, it should be noted that long-term exposure to ionizing radiations, even under defined dose limits, can have adverse health effects. This highlights the crucial role of monitoring radiation workers as at-risk populations who are key workers at the time of health crises such as the current COVID-19 pandemic. Regarding the studied biomarkers, it should be noted that CBCs may not be considered a specific biomarker of radiation exposure. In essence, it is practical to use them to follow up on the overall health of radiation workers. Although the levels of IL-6 are associated with radiation exposure, in order to monitor the health effect of radiation exposure, it is recommended that other cytokines also be measured. Since the balances between pro-inflammatory (or inflammatory) cytokines (for example, IL-1, IL-6, and IL-8) and anti-inflammatory cytokines (for example, IL-4, IL-10, and IL-13) will determine the final health effect.

Acknowledgements The authors would like to thank Dr. Ahmad Faramarzi for his helpful comments.

Author contribution All authors contributed to the study's conception and design. Material preparation was performed by Farshad Bahrami Asl and Mahdi Islami-seginsara. Data collection was performed by Farshad Bahrami Asl, Rasoul Hemmatjo, Mahdi Islami-seginsara, and Mousa Hesam. Analysis was performed by Farshad Bahrami Asl, Mohammad Ebrahimi Kalan, and Vahid Shafiei-Irannejad. The first draft of the manuscript was written by Farshad Bahrami Asl and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Urmia University of Medical Sciences, Project No.: 10237.

Data availability Not applicable.

Declarations

Ethics approval The study protocol and procedures were approved by the institutional ethics committee of the Urmia University of Medical Sciences (#IR.UMSU.REC.1399.221).

Consent to participate Written informed consent was obtained from all participants.

Competing interests The authors declare no competing interests.

References

Abdolmaleki A, Sanginabadi F, Rajabi A, Saberi R (2012): The effect of electromagnetic waves exposure on blood parameters. International Journal of Hematology-Oncology and Stem Cell Research, 13–16

Ahmad IM, Temme JB, Abdalla MY, Zimmerman MC (2016) Redox status in workers occupationally exposed to long-term low levels of ionizing radiation: a pilot study. Redox Rep 21:139–145

Ahmad IM, Abdalla MY, Moore TA, Bartenhagen L, Case AJ, Zimmerman MC (2019) Healthcare workers occupationally exposed to ionizing radiation exhibit altered levels of inflammatory cytokines and redox parameters. Antioxidants 8:12

Aldaham S, Foote JA, Chow H-HS, Hakim IA (2015) Smoking status effect on inflammatory markers in a randomized trial of current and former heavy smokers. Int J Inflamm. 2015

Anandha Lakshmi S, Anandhi Lakshmanan GKP, Saravanan A (2014) Effect of intensity of cigarette smoking on haematological and lipid parameters. J Clin Diagn Res JCDR 8, BC11

Baker N (1990) Exposure to ionizing-radiation from X-rays in the intensive therapy unit St Vincent's Hospital. Nursing Monograph 1:19–26

Baskar R, Dai J, Wenlong N, Yeo R, Yeoh K-W (2014) Biological response of cancer cells to radiation treatment. Front Mol Biosci 1:24

Billings PC, Romero-Weaver AL, Kennedy AR (2014) Effect of gender on the radiation sensitivity of murine blood cells. Gravitational and Space Research: Publication of the American Society for Gravitational and Space Research 2:25

Blakely W, Sandgren D, Nagy V, Kim S-Y, Sigal G, Ossetrova N (2014) Further biodosimetry investigations using murine partial-body irradiation model. Radiat Prot Dosimetry 159:46–51

Buescher ES, Gallin JI (1984) Radiation effects on cultured human monocytes and on monocyte-derived macrophages

Buls N (2016) The implementation of new technologies deserves our particular attention towards radiation safety. Journal of the Belgian Society of Radiology 100

Burton R, Ferguson P, Gray M, Hall J, Hayes M, Smart Y (1983) Effects of age, gender, and cigarette smoking on human immunoregulatory T-cell subsets: establishment of normal ranges and comparison with patients with colorectal cancer and multiple sclerosis. Diagn Immunol 1:216–223

Calò V, Migliavacca M, Bazan V, Macaluso M, Buscemi M, Gebbia N, Russo A (2003) STAT proteins: from normal control of cellular events to tumorigenesis. J Cell Physiol 197:157–168

Cheon BK, Kim CL, Kim KR, Kang MH, Lim JA, Woo NS, Rhee KY, Kim HK, Kim JH (2018) Radiation safety: a focus on lead aprons and thyroid shields in interventional pain management. Korean J Pain 31:244

Citrin DE, Hitchcock YJ, Chung EJ, Frandsen J, Urick ME, Shield W, Gaffney D (2012) Determination of cytokine protein levels in oral secretions in patients undergoing radiotherapy for head and neck malignancies. Radiat Oncol 7:1–6

Criswell T, Leskov K, Miyamoto S, Luo G, Boothman DA (2003) Transcription factors activated in mammalian cells after clinically relevant doses of ionizing radiation. Oncogene 22:5813–5827

Dainiak N (2002) Hematologic consequences of exposure to ionizing radiation. Exp Hematol 30:513–528

Davoudi M, Keikhaei B, Tahmasebi M, Rahim F (2012) Hematological profile change in radiation field workers. Apadana J Clin Res 1:38–44

DavudianTalab A, Farzanegan Z, Mahmoudi F (2018) Effects of occupational exposure on blood cells of radiographers working in Diagnostic Radiology Department of Khuzestan Province. Iran J Med Phys 15:66–70

de Maat MP, Kluft C (2002) The association between inflammation markers, coronary artery disease and smoking. Vascul Pharmacol 39:137–139

Dent P, Yacoub A, Contessa J, Caron R, Amorino G, Valerie K, Hagan MP, Grant S, Schmidt-Ullrich R (2003) Stress and radiation-induced activation of multiple intracellular signaling pathways. Radiat Res 159:283–300

Di Maggio FM, Minafra L, Forte GI, Cammarata FP, Lio D, Messa C, Gilardi MC, Bravatà V (2015) Portrait of inflammatory response to ionizing radiation treatment. J Inflamm 12:1–11

Dorfman AL, Fazel R, Einstein AJ, Applegate KE, Krumholz HM, Wang Y, Christodoulou E, Chen J, Sanchez R, Nallamothu BK (2011) Use of medical imaging procedures with ionizing radiation in children: a population-based study. Arch Pediatr Adolesc Med 165:458–464

Eder K, Baffy N, Falus A, Fulop AK (2009) The major inflammatory mediator interleukin-6 and obesity. Inflamm Res 58:727–736

El-MikkawyEL-Sadek DMMA, EL-Badawy MA, Samaha D (2020) Circulating level of interleukin-6 in relation to body mass indices and lipid profile in Egyptian adults with overweight and obesity. Egypt Rheumatol Rehabil 47:1–7

Faraj K, Mohammed S (2018) Effects of chronic exposure of X-ray on hematological parameters in human blood. Comp Clin Pathol 27:31–36

Faraj K (2021) Occupational exposure of diagnostic technicians to x-ray may change some liver functions and proteins. Iran J Med Phys 18:111–116

Feinendegen LE, Pollycove M, Sondhaus CA (2004) Responses to low doses of ionizing radiation in biological systems. Nonlinearity in Biology, Toxicology, Medicine 2:15401420490507432

Forslund T, Welin M-G, Laasonen L, Weber T, Edgren J (1985) Peripheral blood lymphocyte subsets in radiologists exposed to ionizing radiation. Acta Radiol Oncol 24:415–417

Fujiwara S, Akiyama M, Kobuke K, Hakoda M, Kyoizumi S, Olson GB, Ochi Y, Jones SL (1986) Analysis of peripheral blood lymphocytes of atomic bomb survivors using monoclonal antibodies. J Radiat Res 27:255–266

Gaskin DJ, Thorpe RJ Jr, McGinty EE, Bower K, Rohde C, Young JH, LaVeist TA, Dubay L (2014) Disparities in diabetes: the nexus of race, poverty, and place. Am J Public Health 104:2147–2155

Guan J, Stewart J, Ware JH, Zhou Z, Donahue JJ, Kennedy AR (2006) Effects of dietary supplements on the space radiation-induced reduction in total antioxidant status in CBA mice. Radiat Res 165:373–378

Guirao JJ, Cabrera CM, Jiménez N, Rincón L, Urra JM (2020) High serum IL-6 values increase the risk of mortality and the severity of pneumonia in patients diagnosed with COVID-19. Mol Immunol 128:64–68

Hauck B, Oremek D, Zimmermann R, Ruppel R, Troester B, Eckstein R (2011) Influence of irradiation on in vitro red-blood-cell (RBC) storage variables of leucoreduced RBCs in additive solution PAGGS-M. Vox Sang 101:21–27

Hayata I (2005) Chromosomal mutations by low dose radiation vs. those by other mutagenic factors, International Congress Series. Elsevier, pp. 17–20

Hei TK, Zhou H, Suzuki M (2005) Extranuclear target and low dose radiation risk assessment, International Congress Series. Elsevier, pp. 21–24

Heydarheydari S, Sadeghi S, Almasi A, Sohrabi N (2012) Evaluation of the effects of ionizing radiation on radiation worker's blood parameters of kermanshah hospitals. Journal of Clinical Research in Paramedical Sciences 1

Heydarheydari S, Haghparast A, Eivazi M (2016) A novel biological dosimetry method for monitoring occupational radiation exposure in diagnostic and therapeutic wards: from radiation dosimetry to biological effects. J Biomed Phys Eng 6:21

Ionizing radiation heapm (2016) Ionizing radiation, health effects and protective measures

Jacob P, Rühm W, Walsh L, Blettner M, Hammer G, Zeeb H (2009) Is cancer risk of radiation workers larger than expected? Occup Environ Med 66:789–796

Jha A, Sharma T (1991) Enhanced frequency of chromosome aberrations in workers occupationally exposed to diagnostic X-rays. Mutat Res/Genet Toxicol 260:343–348

Kadhim MA, Moore SR, Goodwin EH (2004) Interrelationships amongst radiation-induced genomic instability, bystander effects, and the adaptive response. Mutat Res/Fundam Mol Mech Mutagen 568:21–32

Kasuba V, Rozgaj R, Jazbec A (2005) Evaluation of chromosomal aberrations in radiologists and medical radiographers chronically exposed to ionising radiation

Kim BH, Kwon Y-J, Ju Y-S, Kim BK, Lee HS, Lee S-g, Chung YK (2017) The work-relatedness at a case of acute lymphoblastic leukemia in a radiation oncologist. Ann Occup Environ Med 29:1–8

Kitsios K, Papadopoulou M, Kosta K, Kadoglou N, Chatzidimitriou D, Chatzopoulou F, Papagianni M, Tsiroukidou K, Malisiovas N (2012) Interleukin-6, Tumor Necrosis Factor alpha and metabolic disorders in Youth. J Endocrinol Metab 2:120–127

Kulkarni S, Singh PK, Ghosh SP, Posarac A, Singh VK (2013) Granulocyte colony-stimulating factor antibody abrogates radioprotective efficacy of gamma-tocotrienol, a promising radiation countermeasure. Cytokine 62:278–285

Linet MS, Slovis TL, Miller DL, Kleinerman R, Lee C, Rajaraman P, Berrington de Gonzalez A (2012) Cancer risks associated with external radiation from diagnostic imaging procedures. CA: a cancer journal for clinicians 62:75–100

Liu G, Gong P, Zhao H, Wang Z, Gong S, Cai L (2006) Effect of low-level radiation on the death of male germ cells. Radiat Res 165:379–389

Ma S, Liu X, Jiao B, Yang Y, Liu X (2010) Low-dose radiation-induced responses: focusing on epigenetic regulation. Int J Radiat Biol 86:517–528

Malenica M, Prnjavorac B, Bego T, Dujic T, Semiz S, Skrbo S, Gusic A, Hadzic A, Causevic A (2017) Effect of cigarette smoking on haematological parameters in healthy population. Med Arch 71:132

Mavragani IV, Nikitaki Z, Souli MP, Aziz A, Nowsheen S, Aziz K, Rogakou E, Georgakilas AG (2017) Complex DNA damage: a route to radiation-induced genomic instability and carcinogenesis. Cancers 9:91

Meeren A, Bertho J-M, Vandamme M, Gaugler M-H (1997) Ionizing radiation enhances IL-6 and IL-8 production by human endothelial cells. Mediators Inflamm 6:185–193

Meo SA (2004) Hematological findings in male x-ray technicians. Saudi Med J 25:852–856

Mezhoud K, Sakly A, Ben Cheikh H, Saïdi M, Edery M (2014) Radiobiology worker risk assessment using stress indicators and proteomics. Int J Low Radiat 9:199–218

Misra RS, Johnston CJ, Groves AM, DeDiego ML, Martin JS, Reed C, Hernady E, Miller J-N, Love T, Finkelstein JN (2015) Examining the effects of external or internal radiation exposure of juvenile mice on late morbidity after infection with influenza A. Radiat Res 184(3):13

Mohammadi M, Gozashti MH, Aghadavood M, Mehdizadeh MR, Hayatbakhsh MM (2017) Clinical significance of serum IL-6 and TNF-α levels in patients with metabolic syndrome. Reports of Biochemistry & Molecular Biology 6:74

Najafi M, Shirazi A, Motevaseli E, Geraily G, Norouzi F, Heidari M, Rezapoor S (2017a) The melatonin immunomodulatory actions in radiotherapy. Biophys Rev 9:139–148

Najafi M, Shirazi A, Motevaseli E, Rezaeyan A, Salajegheh A, Rezapoor S (2017b) Melatonin as an anti-inflammatory agent in radiotherapy. Inflammopharmacology 25:403–413

Nassef M, Kinsara A (2017) Occupational radiation dose for medical workers at a university hospital. Journal of Taibah University for Science 11:1259–1266

Nureddin A, Alatta NO (2016) Effects of long-term exposure to low X-ray on the blood consists of Radiology Department staff of health centers in Libya. Age (year) 37

Ossetrova NI, Condliffe DP, Ney PH, Krasnopolsky K, Hieber KP, Rahman A, Sandgren DJ (2014a) Early-response biomarkers for assessment of radiation exposure in a mouse total-body irradiation model. Health Phys 106:772–786

Ossetrova NI, Sandgren DJ, Blakely WF (2014b) Protein biomarkers for enhancement of radiation dose and injury assessment in nonhuman primate total-body irradiation model. Radiat Prot Dosimetry 159:61–76

Oztas E, Parlak E, Kucukay F, Arhan M, Daglı U, Etik DO, Onder FO, Olcer T, Sasmaz N (2012) The impact of endoscopic retrograde cholangiopancreatography education on radiation exposure to experienced endoscopist: 'trainee effect.' Dig Dis Sci 57:1134–1143

Pietrobelli A, Faith MS, Allison DB, Gallagher D, Chiumello G, Heymsfield SB (1998) Body mass index as a measure of adiposity among children and adolescents: a validation study. J Pediatr 132:204–210

Piotrowski I, Kulcenty K, Suchorska WM, Skrobała A, Skórska M, Kruszyna-Mochalska M, Kowalik A, Jackowiak W, Malicki J (2017) Carcinogenesis induced by low-dose radiation. Radiol Oncol 51:369

Pradhan AD, Manson JE, Rifai N, Buring JE, Ridker PM (2001) C-reactive protein, interleukin 6, and risk of developing type 2 diabetes mellitus. JAMA 286:327–334

Rajaraman P, Doody MM, Yu CL, Preston DL, Miller JS, Sigurdson AJ, Freedman DM, Alexander BH, Little MP, Miller DL (2016) Journal club: cancer risks in US radiologic technologists working with fluoroscopically guided interventional procedures, 1994–2008. Am J Roentgenol 206:1101–1109

Redon CE, Nakamura AJ, Martin OA, Parekh PR, Weyemi US, Bonner WM (2011) Recent developments in the use of γ-H2AX as a quantitative DNA double-strand break biomarker. Aging (Albany NY) 3:168

Rees G, Daniel C, Morris S, Whitehouse C, Binks K, MacGregor D, Tawn E (2004) Occupational exposure to ionizing radiation has no effect on T-and B-cell total counts or percentages of helper, cytotoxic and activated T-cell subsets in the peripheral circulation of male radiation workers. Int J Radiat Biol 80:493–498

Roytblat L, Rachinsky M, Fisher A, Greemberg L, Shapira Y, Douvdevani A, Gelman S (2000) Raised interleukin-6 levels in obese patients. Obes Res 8:673–675

Sabagh M, Chaparian A (2019) Evaluation of blood parameters of the medical radiation workers. Iran J Med Phys 16:439–443

Salek Moghaddam A, Sharafi A, Osati Ashtiani F, Jalali Galousang F (2004) Comparative evaluation of cellular and humoral immunity parameters in radiographers and non radiographers. Razi J Med Sci 10:727–733

Salvato J, Nemerow N, Agardy F (2003) Environmental engineering. Wiley, New Jersey, pp 567–568

Samadi MT, Khorsandi H, Asl FB, Poorolajal J, Tayebinia H (2019) Long-term exposures to Hypersaline particles associated with increased levels of Homocysteine and white blood cells: A case study among the village inhabitants around the semi-dried Lake Urmia. Ecotoxicol Environ Saf 169:631–639

Samadi MT, Khorsandi H, Bahrami Asl F, Poorolajal J, Tayebinia H (2020) The effect of long-term exposures to hypersaline particles originated from drying Urmia hypersaline Lake on the increased cardiovascular risks in the villagers around the Lake. Hum Ecol Risk Assess Int J 26:335–348

Sarbijani HM, Khoshnia M, Marjani A (2016) The association between Metabolic Syndrome and serum levels of lipid peroxidation and interleukin-6 in Gorgan. Diabetes Metab Syndr 10:S86–S89

Sayed D, Abd Elwanis ME, Abd Elhameed SY, Galal H (2011) Does occupational exposure to low-dose ionizing radiation affect bone marrow thrombopoiesis? Int Arch Med 4:1–3

Schaue D, McBride WH (2012) T lymphocytes and normal tissue responses to radiation. Front Oncol 2:119

Schimmöller L, Lanzman R, Dietrich S, Boos J, Heusch P, Miese F, Antoch G, Kröpil P (2014) Evaluation of automated attenuation-based tube potential selection in combination with organ-specific dose reduction for contrast-enhanced chest CT examinations. Clin Radiol 69:721–726

Schubauer-Berigan MK, Wenzl TB (2001) Leukemia mortality among radiation-exposed workers. Occupational Medicine (Philadelphia, Pa.) 16:271–287

Shafiee M, Hoseinnezhad E, Vafapour H, Borzoueisileh S, Ghorbani M, Rashidfar R (2016a) Hematological findings in medical professionals involved at intraoperative fluoroscopy. Global J Health Sci

Shafiee M, Rashidfar R, Borzoueisileh S, Ghorbani M, Vafapour H, Rahimi S (2016b) The Effect of occupational exposure on blood parameters of radiology staffs in Yasuj

Shahid S, Mahmood N, Chaudhry MN, Sheikh S, Ahmad N (2014) Assessment of impacts of hematological parameters of chronic ionizing radiation exposed workers in hospitals. FUUAST J Biol 4:135

Shahid S, Chauhdry MN, Mahmood N, Sheikh S (2015a) Impacts of terrestrial ionizing radiation on the hematopoietic system. Pol J Environ Stud 24:1783–1794

Shahid S, Nawaz Chaudhry M, Mahmood N, Sheikh S (2015b) Mutations of the human interferon alpha-2b gene in brain tumor patients exposed to different environmental conditions. Cancer Gene Ther 22:246–261

Shen Y, Devgan G, Darnell JE, Bromberg JF (2001) Constitutively activated Stat3 protects fibroblasts from serum withdrawal and UV-induced apoptosis and antagonizes the proapoptotic effects of activated Stat1. Proc Natl Acad Sci 98:1543–1548

Shi L, Tashiro S (2018) Estimation of the effects of medical diagnostic radiation exposure based on DNA damage. J Radiat Res 59:ii121–ii129

Singh PK, Wise SY, Ducey EJ, Brown DS, Singh VK (2011) Radioprotective efficacy of tocopherol succinate is mediated through granulocyte-colony stimulating factor. Cytokine 56:411–421

Singh VK, Brown DS, Kao T-C (2010) Alpha-tocopherol succinate protects mice from gamma-radiation by induction of granulocyte-colony stimulating factor. Int J Radiat Biol 86:12–21

Singh VK, Christensen J, Fatanmi OO, Gille D, Ducey EJ, Wise SY, Karsunky H, Sedello AK (2012a) Myeloid progenitors: a radiation countermeasure that is effective when initiated days after irradiation. Radiat Res 177:781–791

Singh VK, Ducey EJ, Fatanmi OO, Singh PK, Brown DS, Purmal A, Shakhova VV, Gudkov AV, Feinstein E, Shakhov A (2012b) CBLB613: a TLR 2/6 agonist, natural lipopeptide of Mycoplasma arginini, as a novel radiation countermeasure. Radiat Res 177:628–642

Singh VK, Fatanmi OO, Singh PK, Whitnall MH (2012c) Role of radiation-induced granulocyte colony-stimulating factor in recovery from whole body gamma-irradiation. Cytokine 58:406–414

Singh VK, Wise SY, Scott JR, Romaine PL, Newman VL, Fatanmi OO (2014) Radioprotective efficacy of delta-tocotrienol, a vitamin E isoform, is mediated through granulocyte colony-stimulating factor. Life Sci 98:113–122

Sun Y, Cheng M-K, Griffiths TRL, Kilian Mellon J, Kai B, Kriajevska M, Manson MM (2013) Inhibition of STAT signalling in bladder cancer by diindolylmethane-relevance to cell adhesion, migration and proliferation. Curr Cancer Drug Targets 13(57):68

Suzuki K, Yamashita S (2012) Low-dose radiation exposure and carcinogenesis. Jpn J Clin Oncol 42:563–568

Szarmach A, Piskunowicz M, Świętoń D, Muc A, Mockałło G, Dzierżanowski J, Szurowska E (2015) Radiation safety awareness among medical staff. Pol J Radiol 80:57

Taqi AH, Faraj KA, Zaynal SA, Hameed AM, Mahmood A-AA (2018) Effects of occupational exposure of x-ray on hematological parameters of diagnostic technicians. Radiat Phys Chem 147:45–52

Tavakkoli M, Moradalizade M, Ananisarab G, Hosseini SM (2012) Evaluation of blood cell count in the radiology staff of Birjand Hospitals in 2011. Modern Care J 9

Tucker JD (2008) Low-dose ionizing radiation and chromosome translocations: a review of the major considerations for human biological dosimetry. Mutation Research/reviews in Mutation Research 659:211–220

Tuschl H, Kovac R, Wottawa A (1990) T-lymphocyte subsets in occupationally exposed persons. Int J Radiat Biol 58:651–659

UNSCEAR-Annex B (2008) Exposures of the public and workers from various sources of radiation. Sources and effects of ionizing radiation: UNSCEAR, 223–463

Whitehead T, Robinson D, Allaway S, Hale A (1995) The effects of cigarette smoking and alcohol consumption on blood haemoglobin, erythrocytes and leucocytes: a dose related study on male subjects. Clin Lab Haematol 17:131–138

Williams PM, Fletcher S (2010) Health effects of prenatal radiation exposure. Am Fam Physician 82:488–493

Wu C-T, Chen M-F, Chen W-C, Hsieh C-C (2013) The role of IL-6 in the radiation response of prostate cancer. Radiat Oncol 8:1–11

Yu H, Pardoll D, Jove R (2009) STATs in cancer inflammation and immunity: a leading role for STAT3. Nat Rev Cancer 9:798–809

Zahm SH, Devesa SS (1995) Childhood cancer: overview of incidence trends and environmental carcinogens. Environ Health Perspect 103:177–184

Zakeri F, Hirobe T (2010) A cytogenetic approach to the effects of low levels of ionizing radiations on occupationally exposed individuals. Eur J Radiol 73:191–195

Zargan S, Seyedmehdi SM, Emami H, Attarchi M, Yazdanparast T (2016) Comparison of blood cells in radiology workers and non-radiation workers staff of a governmental hospital in Tehran. Iran Occup Health 13:31–38

Zielinski JM, Garner MJ, Band PR, Krewski D, Shilnikova NS, Jiang H, Ashmore PJ, Sont WN, Fair ME, Letourneau EG (2009) Health outcomes of low-dose ionizing radiation exposure among medical workers: a cohort study of the Canadian national dose registry of radiation workers. Int J Occup Med Environ Health 22:149