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Field Study

The Effect Occupational Exposure to Ionizing Radiation on the DNA Damage in Peripheral Blood Leukocytes of Nuclear Medicine Personnel

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Abstract: The Effect Occupational Exposure to Ionizing Radiation on the DNA Damage in Peripheral Blood Leukocytes of Nuclear Medicine Personnel: Małgorzata M. Dobrzyńska, *et al*. Department of Radiation Hygiene and Radiobiology, National Institute of Public Health – National Institute of Hygiene, Poland—Objectives: The aim of this study was estimation of DNA strand breaks in leukocytes of peripheral blood of staff in a nuclear medicine department. **Methods:** The exposed group consisted of 46 volunteers and the control group consisted of 40 volunteers. Samples consisting of 1 ml whole blood were collected by venepuncture. DNA damage in leukocytes was detected by alkaline comet assay. **Results:** There was no correlation between the effective dose measured by individual dosimeters and DNA damage and no differences between sexes. The mean level of damage to DNA in people exposed to ionizing radiation was significantly elevated compared with control individuals. The highest value for mean comet tail moment was noted in leukocytes of PET/CT and scintigraphy technicians (1.28 vs. 0.30 for control, p=0.013). The levels of DNA damage in leukocytes of workers in category B (effective dose may exceed 1 mSv/year) were significantly enhanced. The DNA migration of leukocytes in exposed smokers and nonsmokers was similar. In the control group the damage to DNA of leukocytes in smokers was markedly but not significantly higher compared with nonsmokers. **Conclusions:** Occupational exposure to ionizing radiation leads to enhanced levels of reversible DNA damage in leukocytes of nuclear medicine employees. The level of DNA damage depends on the kind of work. Cigarette smoking is related to the increase in DNA damage in unexposed individuals but not in nuclear medicine workers. Radiation seems to be a stronger inducer of DNA damage than smoking. Although most of the DNA damage detected by comet assay is repaired, further improvement of radiation safety should be taken under consideration.
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Key words: DNA damage, Ionizing radiation, Leukocytes, Nuclear medicine, Occupational exposure, Radioisotopes

Ionizing radiation at not only high, but also low chronic doses is known as a mutagenic and carcinogenic agent in mammals, including humans. Medical staff using radiation for diagnostic and therapeutic purposes are potentially at risk of overexposure. Fortunately, due to application of principles of radiological protection, the levels of exposure of medical staff to ionizing radiation have decreased, and they are usually below the limit of 20 mSv/year. However, several studies have shown an increased frequency of micronuclei, chromosomal aberrations, and DNA strand breaks in workers exposed to low doses of ionizing radiation[1–7].

Some medical uses of radiation, such as nuclear medicine, may cause the exposure of staff to higher doses. Nuclear medicine employees are continuously exposed to ionizing radiation in the workplace in spite of use radiation protection devices.

Due to its use of ionizing radiation, the field of nuclear medicine is a unique and significant part of medical diagnostics and patient treatment. According to the European Commission's (EC's) Radiological Protection Section, around 4 to 14% of radiation exposures received by patients as a result of medical

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examinations are caused by nuclear medicine techniques[8].

At present, the public health-care system in Poland has 55 nuclear medicine departmental facilities in operation and there are 8 that are private/nonpublic. These are staffed by 252 doctors, 151 of whom are qualified as nuclear medicine specialists. In addition, 170 highly qualified staff (biologists, chemists, physicists, electronic engineers and IT specialists) provide indispensable scientific/operational support and are vital for the development of nuclear medicine departments. They are mainly responsible for ensuring that all equipment functions effectively and for developing new diagnostic techniques, together with new radiopharmaceuticals. Furthermore, there are approximately 500 other staff at the intermediate-level also involved in nuclear medicine departments, such as technicians, nurses and support workers. For all institutions together, it is estimated that there are 127 gamma cameras, 10 positron emission tomography/computed tomography (PET/CT) scanners and 16 hybrid single-photon emission computed tomography (SPECT/CT) systems in operation. The number of diagnostic procedures performed by medical staff is still growing. In 2000, approximately 117,435 diagnostic procedures were performed, while the current number is around 170,000; up to 38% of the procedures were simple thyroid scintigraphies, 25% were bone scans, 11% were heart scintigraphies and 10% were kidney scans[9].

Nuclear medicine departments use many radiopharmaceuticals for performing diagnosis and treatment whose reference levels are set down in the Ministry of Health Regulation of 18 February 2011[10].

Isotopes must have sufficiently short half-lives and a level of energy from of γ-radiation enabling detection by gamma cameras (e.g., ^{99m}Tc, ^{111}In) or positron emission in PET diagnosis (e.g., ^{18}F, ^{68}Ga, ^{11}C). Therapies using isotopes chiefly consist of the β-emitting ^{89}Sr and ^{90}Y as well as α emitters like ^{223}Ra. Radionuclides emitting both γ- and β-radiation may be used for treatment, diagnosis or monitoring of the course of therapy, e.g., ^{131}I, ^{153}Sm.

The aim of this study was estimation of DNA strand breaks in leukocytes of peripheral blood of staff in the department of nuclear medicine of one hospital in Warsaw, where several kinds of radionuclides and pieces of nuclear medicine equipment are used for radiodiagnosis and radiotherapy.

Materials and Methods

Study subjects and design

The exposed group consisted of 46 members of the staff of the Department of Nuclear Medicine and Oncological Endocrinology, Centre and Institute of Oncology, Warsaw, Poland. The group included doctors, nurses, technicians, radiochemists and administrative staff. People from the examined group had contact with radioisotopes such as ^{191}J, ^{18}F, ^{68}Ga, ^{153}Sm, ^{188}Re, ^{90}Y, ^{177}Lu, ^{89}Sr and ^{99m}Tc, and/or were involved in scintigraphy and PET/CT. Some employees, i.e., administrative staff, had contact with treated patients only. Evaluation of the internal exposure of employees to radioiodine ^{131}I and technetium ^{99m}Tc was described in detail in a paper by Krajewska and Pachocki[11]. Samples were taken during randomly chosen work shifts, since the workers were continuously exposed to radiation. The members of the nuclear medicine staff were employed for 1 to 32 years (mean 8.5 ± 6.7, median 6.0). The control group included 40 nonexposed employees. The majority of them were office workers, including librarians, computer specialists, secretaries and staff of purchasing, finance,, accounting and human resources sections. Moreover, there were several laboratory assistants.

All participants were anonymous volunteers and were informed about the aim of the study and experimental details. They were asked to fill out a questionnaire to get necessary information about sex, age, smoking habits, an exact description of their work, use of therapeutic drugs, previous diagnostic exposure to X-rays and any nuclear medicine examinations. The participants were asked not to use alcohol 24 hours before sampling. There were no restriction regarding smoking. The characteristics of the control and exposed groups are shown in Table 1.

Blood samples

Samples consisting of 1 m*l* whole blood were collected by venepuncture from each donor and drawn into heparinized tubes. Twenty five microliters of whole blood was diluted in 225 μl of RPMI 1640 medium with L-glutamine (Biomedical Industries) for further analyses.

Comet assay

DNA damage in leukocytes was detected by comet assay according to the basic alkaline technique of Singh *et al.*[12] with the following modifications. First, 80 μl of diluted blood was mixed with 80 μl of 1% low melting point agarose (LMPA) (Sigma-Aldrich) and embedded on two microscope slides (80 μl per each) covered previously with normal melting point agarose (NMPA) (Sigma-Aldrich). After 5 minutes of solidification of the agarose at 4°C, a layer of 75 μl of 0.5 % LMPA was added and allowed to solidify at 4°C. The slides were immersed in freshly prepared cold lysing solution overnight at 4°C and then kept in electrophoresis solution for 20 minutes to allow

Table 1. Characteristic on the subjects involved in the study

Parameter	Exposed group	Control group
Sample size	46	40
Males N (%)	7 (15)	10 (25)
Females N (%)	39 (85)	30 (75)
Age (years) ± SD	44.8 ± 9.3	42.3 ± 12.3
Smokers N (%)	14 (30)	10 (25)
Nonsmokers N (%)	32 (70)	30 (75)
Period of exposure, years (mean ± SD)	8.5 ± 6.7	—
Mean effective dose (mSv ± SD)	0.30 ± 0.23	—

the unwinding of DNA. Alkaline electrophoresis was carried out for 20 minutes at 300 mA and 24 V. After neutralization, slides were stained with ethidium bromide (Sigma-Aldrich) solution (20 μg/m*l*). Slides were evaluated using a fluorescence microscope (Nikon, Japan). Randomly selected images were recorded, and images of 100 cells from each individual were analyzed using the CASP image-analysis software[13]. The following parameters for further evaluation were chosen: comet tail moment (CTM) and percent of DNA in the comet tail (% DNA CT).

Statistical analysis

Our data failed the normality test and equal variance test required for parametric analysis of variance statistics. A nonparametric Kruskal-Wallis test was used for multiple comparisons. Pair-wise comparisons of all treatment groups versus the control group using a Mann-Whitney test were conducted. p values less than 0.05 were considered significant.

Results

Both the control and exposed groups were similar in relation to age, sex and smoking habit (Table 1).

The results of the study are shown in Table 2 and in Fig. 1 to 5.

The effect of personal effective doses on the level of DNA damage

There were no correlations between effective yearly doses measured by individual dosimeters and DNA damage. For instance, there were 23 individuals receiving a mean yearly dose of 0.2 mSv, and their CTMs varied from 0.004 to 5.4 (Fig. 1). Only six people had received yearly doses over 0.5 mSv/year. These individuals included two scintigraphy nurses, who were involved in diagnostic procedures, and four radiochemists, who prepared radiopharmaceuticals for scintigraphy and PET/CT procedures. DNA damage in the leukocytes of the majority of the individuals receiving the highest dose was extremely low, except

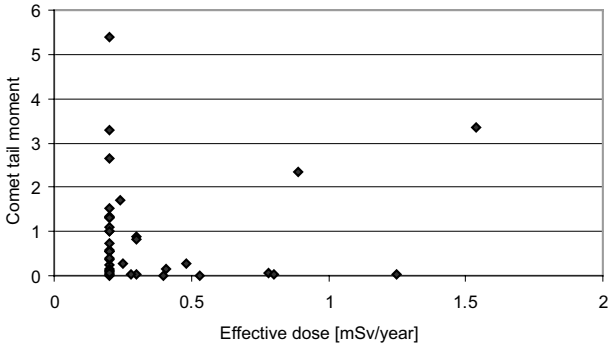

Fig. 1. Distribution of comet tail moment values depending on radiation dose [mSv] measured by personal dosimeter.

in two of them. So, the mean CTM after excluding the valueas for the above six individuals was 0.89 ± 1.04 vs. 0.90 ± 1.09 for all individuals.

The effects of kind of work on the level of DNA damage

There were significant differences between the damage to genetic material of leukocytes in the control and exposed groups; however, there was variability between individuals in both groups (Table 2, Fig. 2). The mean values for % DNA CT in the control group varied from 0.15 to 2.66, whereas in exposed group, they varied from 0.6 to 7.55. Similarly, CTM varied in the control group from 0.006 to 2.26 and in the exposed group from 0.004 to 5.40. The mean % DNA CT of the exposed group exceeded twice that of the control group, whereas the mean CTM of the nuclear medicine staff was 2.3 times higher than that of the control group (Table 2, Fig. 2). The kind of work was connected to the level of DNA damage in leukocytes. The mean values for % DNA CT and CTM of technicians involved in scintigraphy and PET/CT were the highest and markedly exceeded the mean values for both parameters in the other exposed groups. Only the results for this subgroup were significantly different compared with

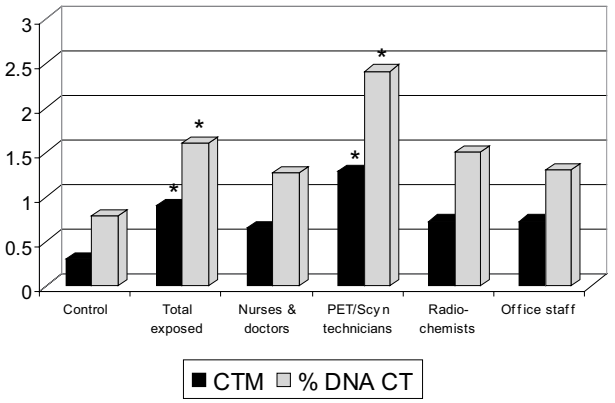

Fig. 2. Damage to DNA of peripheral blood leukocytes in different groups of nuclear medicine staff.
CTM – comet tail moment; % DNA CT – percent of DNA in comet tail; *p<0.05 compared with the control by Mann-Whitney test.

the control. Similar results were obtained for median values (Table 2, Fig. 2).

The effects of category and period of work on the level of DNA damage

The mean values for both % DNA CT and CTM of staff in categories A (workers who may be exposed to an effective dose exceeding 6 mSv in one year) and B (workers who may be exposed to an effective dose exceeding 1 mSv in one year) were similar, but the median values were markedly higher for staff in category B. The DNA damage of leukocytes in workers of category B was significantly different from that in the control (Table 2, Fig. 3). The DNA damage of white blood cells was not dependent on the period of work of the exposed staff (less or more than 10 years); however the level of DNA damage in white blood cells was significantly elevated in both groups of nuclear medicine employees compared with the control group (Table 2).

The effect of sex and smoking habit on the level of DNA damage in control and exposed groups

There were no significant differences between DNA damage in leukocytes of females and males among the control and exposed subjects (Table 2). The level of DNA damage in white blood cells of exposed women was significantly higher compared with the control females, whereas the differences were not significant when compared eith the results of control and exposed males (Table 2).

The damage to DNA of leukocytes in the exposed smokers and nonsmokers was similar, and surprisingly, the median values for % DNA CT and CTM for smokers were lower. In the control group, both the mean and median values of CTM and % DNA CT were markedly but not significantly increased in the group of smokers (Table 2, Fig. 4). There were no significant differences between the levels of damage to DNA in the control and exposed smokers. On the other hand, in nonsmokers, both CTM and % DNA CT were significantly elevated in the exposed individuals (Table 2).

The effect of age on the level of DNA damage in the control and exposed groups

There were no significant differences between the levels of damage to DNA of white blood cells in individualas from different age subgroups both in the control and exposed groups. When comparing the individuals from the exposed and control age subgroups, significant increases in the values of both CTM and % DNA CT were observed only when people were older than 50 years.

Discussion

Single cell gel electrophoresis (comet assay) is a well established test recommended for in vivo and in vitro testing of chemical and physical agents for genotoxicity[14, 15].

DNA is considered a primary target of ionizing radiation acting both directly or indirectly. The comet assay is often used to quantity DNA damage, which is a marker for radiosensitivity[16]. The majority of DNA damage is repaired within minutes or hours after induction[12, 17, 18], but some is not repaired or not repaired properly. Both induction of mutations and unsuitable DNA repair may be considered an early indicator of cancer risk[19].

Ionizing radiation is widely used in medicine for treatment of patients and for diagnosis. Medical and supportive staff in the field of nuclear medicine are continuously exposed to ionizing radiation, usually at low doses. The exposure takes place during handling and administration of solutions containing radioisotopes, during monitoring and nursing of patients[20, 21], and during service of devices for scintigraphy and PET/CT[22, 23]. Moreover, patients who receive isotopes became a source of radiation for other people including family and hospital staff not directly involved in the therapy.

In the current study, interindividual variability among exposed and control individuals was observed. A similar response has also been noted previously[1, 3, 4, 24–26]. The reason for such an effect might be differences in genomic sensitivity[4, 24, 27] or the combination of genetic and nongenetic factors[28].

In our study, there were no significant differences between damage to DNA in females compared with males in both the control and exposed groups. Both

Table 2. Comparison of mean comet tail moments (CTM) and mean percent of DNA in comet tail (% DNA CT) between different groups of employees

Name of group	CTM			% DNA CT		
	Mean ± SD	Median	*p*	Mean ± SD	Median	*p*
Controls	0.30 ± 0.44	0.12		0.78 ± 0.54	0.63	
Total nuclear medicine staff	0.90 ± 1.09*	0.57	0.002	1.60 ± 1.50*	1.12	0.005
Nurses/doctors	0.65 ± 0.71	0.50	0.152	1.27 ± 1.09	1.10	0.229
Scintigraphy/PET technicians	1.28 ± 1.44*	1.06	0.013	2.41 ± 1.89*	1.84	0.001
Radiochemists	0.72 ± 1.47	0.07	0.732	1.51 ± 2.13	0.51	0.914
Administrative staff	0.72 ± 0.61	0.59	0.097	1.31 ± 0.92	1.04	0.052
Control women	0.32 ± 0.49	0.12		0.74 ± 1.93	0.63	
Control men	0.27 ± 0.28	0.11	0.712	0.90 ± 0.47	0.74	0.174
Exposed women	0.91 ± 1.08	0.59		1.62 ± 1.50	1.13	
Exposed men	0.84 ± 1.18	0.27	0.561	1.49 ± 1.65	0.51	0.669
Control women	0.32 ± 0.49	0.12		0.74 ± 1.93	0.63	
Exposed women	0.91 ± 1.08*	0.59	0.003	1.62 ± 1.50*	1.13	0.013
Control men	0.27 ± 0.28	0.11		0.90 ± 0.47	0.74	
Exposed men	0.84 ± 1.18	0.27	0.526	1.49 ± 1.65	0.51	0.098
Controls	0.30 ± 0.44	0.12		0.78 ± 0.54	0.63	
Staff category A	0.72 ± 1.47	0.07	0.732	1.51 ± 2.13	0.51	0.914
Staff category B	0.91 ± 1.09*	0.59	0.001	1.58 ± 1.48*	1.13	0.005
Control	0.30 ± 0.44	0.12		0.78 ± 0.54	0.63	
Exposed <10 years	0.89 ± 1.02*	0.40	0.010	1.60 ± 1.45*	1.12	0.021
Exposed >10 years	0.92 ± 1.24*	0.66	0.007	1.61 ± 1.71*	1.05	0.031
Control smokers	0.57 ± 0.73	0.23		1.13 ± 0.77	0.90	
Control nonsmokers	0.23 ± 0.26	0.11	0.208	0.65 ± 0.39	0.58	0.084
Exposed smokers	0.89 ± 1.43	0.31		1.64 ± 1.93	0.86	
Exposed nonsmokers	0.91 ± 0.93	0.78	0.527	1.58 ± 1.32	1.44	0.775
Control smokers	0.57 ± 0.73	0.23		1.13 ± 0.77	0.90	
Exposed smokers	0.89 ± 1.43	0.31	0.661	1.64 ± 1.93	0.86	0.639
Control nonsmokers	0.23 ± 0.26	0.11		0.65 ± 0.39	0.58	
Exposed nonsmokers	0.91 ± 0.93*	0.78	0.001	1.58 ± 1.32*	1.44	0.001
Control age below 35	0.38 ± 0.60	0.11	0.721[a]	0.88 ± 0.71	0.58	0.952[a]
Control age 36–50	0.21 ± 0.23	0.10	0.852[b]	0.77 ± 0.40	0.64	0.820[b]
Control age over 50	0.30 ± 0.36	0.22	0.835[c]	0.72 ± 0.46	0.62	0.633[c]
Exposed age below 35	1.00 ± 1.11	1.12	0.469[a]	1.80 ± 1.52	1.91	0.342[a]
Exposed age 36–50	0.68 ± 0.90	0.27	0.686[b]	1.27 ± 1.24	0.81	0.978[b]
Exposed age over 50	1.08 ± 1.29	0.89	0.120[c]	1.92 ± 1.74	1.62	0.103[c]
Control age below 35	0.38 ± 0.60	0.11		0.88 ± 0.71	0.58	
Exposed age below 35	1.00 ± 1.11	1.12	0.114	1.80 ± 1.52	1.91	0.245
Control age 36–50	0.21 ± 0.23	0.10		0.77 ± 0.40	0.64	
Exposed age 36–50	0.68 ± 0.90	0.27	0.469	1.27 ± 1.24	0.81	0.230
Control age over 50	0.30 ± 0.36	0.22		0.72 ± 0.46	0.62	
Exposed age over 50	1.08 ± 1.29*	0.89	0.006	1.92 ± 1.74*	1.62	0.006

* $p<0.05$ compared with the corresponding control by the Mann-Whitney test. [a] Row 1 vs. row 2. [b] Row 1 vs. row 3. [c] Row 2 vs. row 3.

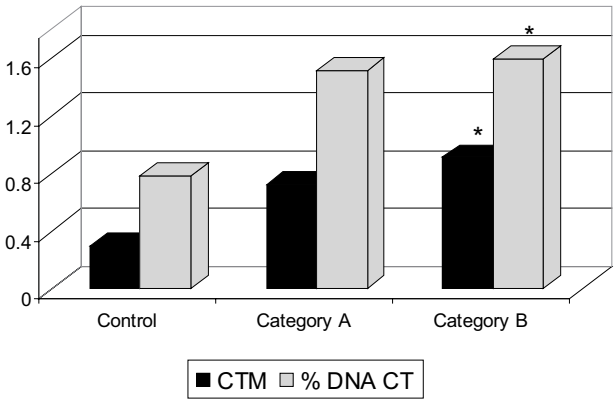

Fig. 3. Damage to DNA of peripheral blood leukocytes in nuclear medicine staff depending on category of work. Category A, workers who may be exposed to an effective dose exceeding 6 mSv in one year; category B, workers who may be exposed to an effective dose exceeding 1 mSv in one year.
CTM – comet tail moment; % DNA CT – percent of DNA in comet tail; *$p<0.05$ compared with the control by Mann-Whitney test.

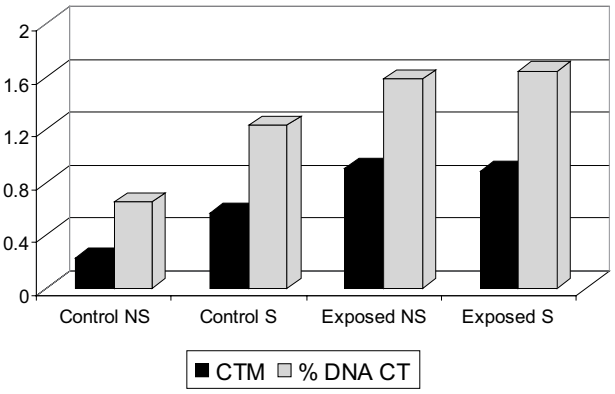

Fig. 4. Damage to DNA of peripheral blood leukocytes in smokers (S) and nonsmokers (NS) among workers in the control and exposed groups.
CTM – comet tail moment; % DNA CT – percent of DNA in comet tail.

similar[1, 4] and opposite[1, 24] results have been noted by other authors.

The current results showed that occupational exposure to ionizing radiation caused significant DNA damage in peripheral blood leukocytes of nuclear medicine staff in total. Interestingly, a strong difference was noted between control and exposed females, but this was not observed for males. The majority of nuclear medicine department employees are supplied individual dosimeters, and the effective doses are recorded. We did not find a direct correlation between the dose measured by an individual dosimeter and DNA migration. Moreover, some members of the administrative staff (not monitored individually) had quite high levels of DNA damage in leukocytes. The reason for the above finding might be a difference in the susceptibility of the genetic material of individuals to effects induced by ionizing radiation. The above mentioned lack of correlation was also observed previously[3, 4, 29, 30]; however, correlation has been reported prevously[31].

This present study showed the significantly highest level of DNA damage in leukocytes of scintigraphy/PET technician compared with the other exposed groups. Similar results were noted by Undegar *et al.*[32] but not by Kopjar and Garaj-Vrhovac[33] and Garaj-Vrhovac and Kopjar[3].

The reason for high migration of DNA of leukocytes in the technicians involved in scintigraphy and PET/CT might be that they are working for almost their full shifts very close proximaly to patients to whom isotopes have been applied, monitoring patients during investigations and finally helping the patients to leave the scan bed. The levels of damage to DNA in the leukocytes of the members of the other groups of nuclear medicine staff seem a little confusing, but there are some things that can help in understanding such results. First, the individuals handling radioisotopes and radio pharmaceuticals used appropriate materials for self-prevention like hoots, gloves and masks, and this may explain the relatively low damage to DNA in radiochemists. Also, nurses and doctors seem to be at higher risk due to direct contact with patients to whom isotopes have been applied. The patients after application of radioisotopes seem to be the most important mobile sources of radiation. The results showing relatively high DNA migration in white blood cells of administrative workers seem to support this hypothesis.

Surprisingly, the individuals in work category B, but not those in work category A showed significantly higher DNA migration compared with the control. One of the explanations for such an effect might be the adaptive response to DNA of white blood cells, which was observed previously in vitro[34, 35].

The period of exposure to ionizing radiation in the workplace was not associated with the level of DNA damage in leukocytes, although both individuals employed less and more than 10 years showed significantly increased migration of DNA in leukocytes. No differences is opposite to earlier results of Undeger *et al.*[32].

We observed no significant enhancement of the level of DNA migration in leukocytes of the smoking control individuals and no differences between DNA damage in the smokers and nonsmokers among occupationally exposed individuals, but the level of damage to DNA in leukocytes of the control

nonsmokers was significantly lower than of exposed nonsmokers. Majority of earlier studies noted no significantly increased levels of DNA migration in smokers exposed to ionizing radiation[4, 30, 36, 37] however, Undeger *et al.*[32] reported a contradictory result. The influence of smoking habit on the DNA migration in control individuals was observed by other authors[4, 24, 29], but another author did not observe such correlation[26].

The current study showed no difference in damage to DNA of leukocytes between age groups both in the case of control and exposed individuals. Previously higher DNA damage was noted in lymphocytes of individuals over 60 years of age by Singh *et al.*[38]. However, among our exposed group, there were no individuals older than 60 years of age and among the control individuals, there was only one woman, who was 66 years old. The only difference observed was significantly higher damage to DNA of leukocytes in the exposed individuals over the age of 50 years compared with control persons of the same age. This finding is in line with results of an earlier paper[39], which reported that an age-related increase in DNA damage was observed after irradiation of human lymphocytes in vitro.

The above results showed that enhanced damage to DNA in leukocytes of workers occupationally exposed to ionizing radiation still occurs in spite of use of radiation protection devices. We are going to continue similar research on a larger group of employees.

Conclusions

Occupational exposure to ionizing radiation leads to an enhanced level of reversible DNA damage in peripheral blood leukocytes of nuclear medicine employees. The level of DNA damage depends on the kind of work. Cigarette smoking is related to an increase in DNA damage in unexposed individuals, but not in case of workers exposed to ionizing radiation. Radiation seems to be a stronger inducer of DNA damage than smoking. Although most of the DNA damage detected by the comet assay is repaired, further improvement of hospital radiation safety should be taken under consideration.

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References

1) Wojewódzka M, Kruszewski M, Iwaneńko T, Collins A, Szumiel I. Application of the comet assay for monitoring DNA damage in workers exposed to chronic low-dose irradiation - I. Strand breakage. Mutat Res 1998; 416: 21–35.
2) Cardoso RS, Takahashi-Hyodo S, Peitl P Jr, Ghilardi-Neto T, Sakamoto-Hojo ET. Evaluation of chromosomal aberrations, micronuclei and sister chromatid exchanges in hospital workers chronically exposed to ionizing radiation. Teratog Carcinog Mutagen 2001; 21: 431–9.
3) Garaj-Vrhovac V, Kopjar N. The alkaline Comet assay as biomarker in assessment of DNA damage in medical personnel occupationally exposed to ionizing radiation. Mutagenesis 2003; 18: 265–71.
4) Kopjar N, Garaj-Vrhovae V. Assessment of DNA damage in nuclear medicine personnel—comparative study with the alkaline comet assay and the chromosomal aberration test. Int J Hyg Environ Health 2005; 208: 179–91.
5) Sari-Minodler I, Orsiere T, Auquier P, Martin F, Botta A. Cytogenetic monitoring by use of micronucleus assay among hospital workers exposed to low doses of ionizing radiation. Mutat Res 2007; 629: 111–21.
6) Zakeri F, Hirobe T. A cytogenetic approach to the effects of low levels of ionizing radiations on occupationally exposed individuals. Eur J Radiol 2010; 73: 191–5.
7) Bouraoui S, Mougou S, Drira A, et al. A cytogenetic approach to effects of low levels of ionizing radiation (IR) on the exposed Tunisian hospital workers. Int J Occup Med Environ Health 2013; 26: 144–54.
8) European Commission Unit H.4 – Radiation Protection. Review of national surveys of population exposure from nuclear medicine examinations in eight European countries. Report No. 154, Annex 2- Dose Datamed Report 1a, Directorate-General for Energy and Transport, Luxembourg, 2008.
9) Pachocki KA, Sackiewicz-Słaby A. Determining the current status and potential of nuclear medicine in Poland. Rocz Panstw Zakl Hig 2013; 64: 243–50.
10) [Regulation of 18 February 2011 on safe use of ionising radiation for all types of medical exposures]. Dz. U. 2011. no. 51, pos. 265 (in Polish).
11) Krajewska G, Pachocki KA. Assessment of exposure of workers to ionizing radiation from radioiodine and technetium in nuclear medicine departmental facilities. Med Pr 2013; 64 (in press).
12) Singh NP, Mc Coy, Tice RR, Schneider EL. A simple technique for quantization of low level of DNA damage in individual cells. Exp Cell Res 1988; 175: 184–91.
13) Końca K, Lankoff A, Banasik A, et al. Cross-

platform public domain PC image-analysis program for comet assay. Mutat Res 2003; 534: 15–20.
14) Tice RR, Agurell E, Anderson D, et al. Single cell gel/comet assay guidelines for in vitro and in vivo genetic toxicology testing. Environ Mol Mutagen 2000; 35: 206–21.
15) Valverde M, Rojas E. Environmental and occupational biomonitoring using the Comet assay. Mutat Res 2009; 681: 93–109.
16) McKenna DJ, McKeown SR, McKelvey-Martin VJ. Potential use of the comet assay in the clinical management of cancer. Mutagenesis 2008; 23: 183–90.
17) Price A. The repair of ionizing radiation-induced damage to DNA. Cancer Biol 1993; 4: 61–71.
18) Tice RR. The single cell gel/comet assay: a microgel electrophoretic technique for the detection of DNA damage and repair in individual cells. In: Philips DH, Vennit S, editors. Environmental Mutagenesis Bioscientific. Oxford (UK); 1995. p. 31–9.
19) Benhamou S, Sarasin A. Variability in nucleotide excision repair and cancer risk: a review. Mutat Res 2000; 462: 149–58.
20) Bozkurt G, Yuksei M, Karabogaz G, et al. Sister chromatid exchanges in lymphocytes of nuclear medicine physicians. Mutat Res 2003; 535: 205–13.
21) Seierstad T, Stranden E, Bjering K, et al. Doses to nuclear technicians in dedicated PET/CT centre utilizing ^{18}F fluorodeoxyglucose (FDG). Radiat Prot Dosimetry 2007; 123: 246–9.
22) Carson KJ, Young VA, Cosgrove VP, Jarritt PH, Haunsell AR. Personnel radiation dose considerations in the use of an integrated PET-CT scanner for radiotherapy treatment planning. Br J Radiol 2009; 82: 946–9.
23) Demir M, Demir B, Yasar D, et al. Radiation doses to technologists working with F-18-FDG in a PET center with high patient capacity. Nukleonika 2010; 55: 107–12.
24) Betti C, Davini T, Giannessi L, Loprieno N, Barale R. Microgel electrophoresis assay (comet test) and SCE analysis in human lymphocytes from 100 normal subjects. Mutat Res 1994; 307: 323–33.
25) Morillas MJ, Guillamet E, Surralles J, Creus A, Marcos R. Spontaneous and induced genetic damage in T lymphocyte subsets evaluated by the comet assay. Mutat Res 2002; 514: 39–48.
26) Speit G, Witton-Davies T, Heepchantree W, Trenz K, Hoffman H. Investigations on the effect of cigarette smoking in the comet assay. Mutar Res 2003; 542: 33–42.
27) Frenzilli G, Betti C, Davini T, et al. Evaluation of DNA damage in leukocytes of ex-smokers by single cell gel electrophoresis. Mutat Res 1997; 375: 117–23.
28) Fachin AL, Mello SS, Sandrin-Garcia P, et al. Gene expression profiles in radiation workers occupationally exposed to ionizing radiation. J Radiat Res 2009; 50: 61–71.
29) Barquinero JF, Barrios L, Caballin MR, et al. Cytogenetic analysis of lymphocyte from hospital workers occupationally exposed to low levels of ionizing radiation. Mutat Res 1993; 286: 275–79.
30) Maluf SW, Passos DF, Bacelar A, Speit G, Erdtmann B. Assessment of DNA damage in lymphocytes of workers exposed to X-radiation using the micronucleus test and the comet assay. Environ Mol Mutagen 2001; 38: 311–5.
31) Martinez A, Coleman M, Romero-Talamas CA, Frias S. An assessment of immediate DNA damage to occupationally exposed workers to low dose radiation by using the comet assay. Rev Invest Clin 2010; 62: 23–30.
32) Undeger U, Zorlu AF, Basaran N. Use of alkaline comet assay to monitor DNA damage in technicians exposed to low-dose radiation. J Occup Environ Med 1999; 41: 693–8.
33) Kopjar N, Garaj-Vrhovae V. The assessment of primary DNA damage in peripheral blood leukocytes of nuclear medicine personnel. In: Proceedings of the 11th International Radiation Protection Association: 2004 May 23–28; Madrid, Spain.
34) Bai Y, Chen D. Accumulative effect of two low doses of irradiation inducting an adaptative response in human lymphocytes. Mutat Res 1993; 302: 191–6.
35) Barquinero JF, Barrios L, Caballin MR, et al. Decreased sensitivity in the cytogenetic effects of bleomycin in individuals occupationally exposed to ionizing radiation. Mutat Res 1996; 354: 81–6.
36) Andreoli C, Rossi S, Leopardi P, Crebelli R. DNA damage by hydroquinone in human white blood cells analysis by alkaline single-cell gel electrophoresis. Mutat Res 1999; 438: 37–45.
37) Wojewódzka M, Kruszewski M, Iwaneńko T, Collins A, Szumiel I. Lack of adverse effect of smoking habit on DNA stand breakage and base damage as revealed by the alkaline comet assay. Mutat Res 1999; 440: 19–25.
38) Singh NP, Danner DB, Tice RR, et al. Basal DNA damage in individual human lymphocytes with age. Mutat Res 1991; 256: 1–6.
39) Singh NP, Danner DB, Tice RR, Brant L, Schneider EL. DNA damage and repair with age in individual human lymphocytes. Mutat Res 1990; 237: 123–30.