УДК 617.741-004.1-02:614.876

Comparative analysis of lens structural changes in ex-clean-up workers exposed to radiation from Chornobyl versus non-exposed individuals

Elza Grisle [1, 2]; Arturs Zemitis [1, 2]; Inesa Markevica [1, 2]; Maksims Zolovs [1, 3]; Guna Laganovska [1, 2]

[1] Riga Stradins University
Riga (Latvia)

[2] Pauls Stradins Clinical University Hospital
Riga (Latvia)

[3] Daugavpils University, Institute of Life Sciences and Technology
Daugavpils (Latvia)

Purpose. *The purpose of this research was to measure lens posterior cortex thickness and compare it between Chornobyl ex-clean-up workers and healthy individuals to determine whether Chornobyl ex-clean-up workers have a higher prevalence of posterior cortex cataract.*

Materials and methods. *The study was conducted on 32 eyes of healthy, non-exposed individuals, 32 eyes of individuals who worked only in Chornobyl City, and 16 eyes of individuals who worked on the roof of the reactor. All measurements were performed using a Heidelberg Anterion device. Statistical analyses were performed using Jamovi statistical software.*

Results. *The results showed that those who had worked on the roof of the reactor had a significantly higher percentage of their lens occupied by the posterior cortex (median 17.3%, IQR 15.5–18.5%) compared to both the controls and city workers. Therefore, they also have a higher prevalence of posterior subcapsular cataracts (p<0.001).*

Conclusion. *Exposure to increased radiation doses can cause alterations in various body structures, including the lens. Numerous studies have posited that heightened radiation exposure can induce substantial alterations in ocular structural integrity. Conversely, other studies have yielded results that exhibit higher degrees of uncertainty and ambiguity.*

Keywords:

Ionising radiation, nuclear power plant, radiation accident, cataract

Introduction. Radiation is the emission of energy as electromagnetic waves or moving subatomic particles. Every day, all organisms on Earth encounter solar ultraviolet radiation [1]. This radiation can cause some physiological age-related changes in the human lens [1-3], including altered cation transport, increased permeability, and altered biosynthesis, which lead to age-related cataracts [4]. Age-related changes in lens structure due to ultraviolet radiation usually progress slowly and depend on the duration of exposure [5], which explains why age-related cataracts are more common among the elderly. Ultraviolet radiation waves are longer, and therefore this type of radiation is relatively harmless [6]. Other types of radiation, such as ionising radiation, have shorter wavelengths. Radiation with a shorter wavelength is more dangerous; this type of energy source is used in radiology during medical examinations, in radiation therapy when treating cancer, and in nuclear power plants. Nuclear accidents have the potential to release significant levels of hazardous ionising radiation into the environment [7].

Epidemiological studies among Chornobyl clean-up workers, atomic bomb survivors, astronauts, residents of contaminated buildings, radiological technicians, and recent surveys of staff in interventional rooms indicate an increased incidence of lens opacities at doses below 1 Gy[8]. However, the critical dose of radiation exposure that can cause significant lens opacities and vision-impairing cataracts remains unclear [9]. Among future epidemiological research directions, the most important research need is adequate studies on vision-impairing cataracts after protracted radiation exposure[10].

There are various types of radiation with variable tissue and substance penetration abilities [11, 12].

- Alpha radiation
- Beta radiation
- Gamma radiation and X-rays
- Neutron radiation

Among these types of radiation, alpha and beta radiation do not usually cause deep tissue damage. On the contrary, gamma and neutron radiation can penetrate the skin deep into body tissues and cause severe damage [13, 14]. These types of radiation can be emitted during nuclear incidents or conflicts involving nuclear weapons [15].

Ex-clean-up workers in Chornobyl and Pripyat were definitely exposed to an increased intensity of ionising radiation. The distribution of radioactive elements is uneven; therefore, it is difficult to determine the exact dose and type of radiation each individual received [16]. However, there have been studies determining the types of radioactive elements and their intensity that were more commonly distributed inside and on the roof of the reactor, in the territory near the reactor, in the residential areas of Chornobyl and Pripyat, and in territories further away from Ukraine after the accident in the early morning of April 26 in 1986 [17]. According to research, the median lethal dose of radiation for humans is around 3 Gy [18]. 1 Gy equals 100 roentgens [19].

Approximately one hour after the explosion, the radiation level in reactor unit 4 at Chornobyl reportedly exceeded 200 roentgens per hour. Radioactive fission products released into the atmosphere by the reactor explosion initiated the ionising radiation at Chornobyl. These products included several types of radioactive isotopes (such as iodine and caesium, along with gases like xenon-133). Subsequent estimates indicated that the debris surrounding the damaged reactor emitted radiation levels of approximately 10,000 roentgens per hour, sufficient to kill human cells or cause severe malfunctions. Exposure to 500 roentgens over a five-hour period was deemed lethal [20].

The common radioactive element in Chornobyl and Pripyat after the accident was 137Cs, and its highest concentration was on the roof and inside the reactor, as well as in the area 30 km around the reactor [21]. Retrospective reconstruction of external gamma exposure doses was performed based on the results of direct dose rate measurements performed during the accident and the individual behaviour/migration histories of the evacuees. Individual doses were reconstructed for 30,586 evacuees from the city of Pripyat and settlements within the 30-km zone. The average effective dose resulting from external irradiation in this cohort was estimated to be 15 mSv, although individual values varied in an extremely wide range (0.1–383 mSv). The collective dose of the entire evacuated population was 1,300 person-Sv [22].

Another very common radioactive element in the cities was 131I. The mean dose from inhalation of 131I for early Chornobyl cleanup workers was estimated to be 0.18 Gy [23]. The water in the Pripyat River was most heavily contaminated with 90Sr and 137Cs elements, which were further distributed to the Chornobyl floodplain and further [17]. In addition, in other research on radiation emissions in territories further away from Chornobyl and Ukraine, 137Cs was the most found radioactive agent. In Austria, it was found that 131I was also a common element [24]. In another study in the UK, it was also found that the distribution of 131I was particularly high, particularly in food products containing milk [25]. The long-term consequences of the Chornobyl disaster remain unclear [20, 26]. Despite the new shelter in place over damaged reactor unit 4, the area around the nuclear plant will not be safe for human habitation for at least another 20,000 years. For example, Plutonium-239 – traces of which were found as far away as Sweden – has a half-life period of 24,000 years.[20]

Exposure to higher radiation doses can also cause damage to various ocular structures [27, 28]. Different ocular structures have different susceptibilities to radiation-induced damage [29], and the lens is considered one of the most radiosensitive tissues in the human body [30]. It has been assumed that high-dose neutron radiation can cause lens fibres to migrate towards the posterior surface of the lens, leading to posterior subcapsular cataract formation [31, 32].

The UACOS-Ukrainian/American Chornobyl ocular study, similar research regarding lens changes due to exposure to increased intensity of radiation, also has presented results showing a trend towards a dose-dependent loss of posterior subcapsular (PSC) transparency on an inter-subject basis. It is important to note that, characteristically, radiation cataracts first appear in the PSC region of the lens. In addition to observations on the effect of dose on lenticular transparency, there is a measurable effect of radiation on the dimension of the anteroposterior axis of the lens. Until now, only anecdotal evidence has been available regarding radiation effects on lens size [33].

Previous studies have also assumed that increased radiation doses can lead to retinal vessel angiosclerosis, neovascularization of the anterior chamber angle, and secondary glaucoma formation, as well as increase the accumulation of pigment in the trabecular meshwork. Previous studies on this topic have assumed that eye changes can predict further possible neurological and other systemic radiation-induced damage [27].

It is difficult to determine the exact radiation dose each individual receives in the setting of a nuclear accident because the distribution of radiation can be uneven and the location of each individual during the accident can vary [34, 35].

This study was conducted to determine whether individuals (ex-clean-up workers) who were exposed to increased radiation intensity during the Chornobyl nuclear accident had an increased prevalence of posterior cortex cataracts. The patients were compared with non-exposed individuals. Among the ex-clean-up workers, the patients were divided into groups based on their duration of stay in the territory, types of work they performed, whether they worked only in the city or also on the roof near the reactor or inside the reactor unit, and systemic and ocular complaints they had during their stay in Chornobyl. Patients in the research were ex-clean-up workers who stayed in the territory during the period of 1986–1989. None of the people included in the study stayed longer than 6 months.

Materials and Methods

This study was conducted on a patient group aged 55–70 years. Participants were divided into three groups for comparison:

• Control Group: 32 eyes from 20 healthy individuals with a median age of 67 years (IQR 61–69 years).

• Cleanup Workers (Non-Roof): 32 eyes from 17 Chornobyl cleanup workers who worked in the vicinity but not on the roof or inside the reactor unit, with a median age of 63.5 years (IQR 60–66 years).

• Cleanup Workers (Roof/Inside the reactor unit): 16 eyes from 8 Chornobyl cleanup workers who worked on the roof near the reactor or inside the reactor unit, and had a median age of 61 years (IQR 59–61 years).

None of the participants had official information about the doses of external radiation they received during work. Most of the patients in this research stayed in the territories of Chornobyl and Pripyat during 1986–1989. The duration of stay for the patients in the research was a minimum of 1 month and a maximum of 6 months. The actual thickness of the posterior lens cortex, percentage of total lens thickness occupied by the posterior lens cortex, and total lens thickness were compared between the groups (figures 1 and 2). Additional information about the patient's duration of stay in Chornobyl and the type of work they performed was collected, as well as information about any systemic or ocular complaints that started during their stay in the territory. All measurements were performed using the Heidelberg Anterion device; the programme "cataract" was selected, and the entire lens thickness was measured automatically. The calliper was then adjusted from the anterior lens pole towards the beginning of the hyperechoic area in the posterior pole (recognised as the posterior cortex), and the posterior cortex thickness was determined. The results were collated into tables and diagrams. Permission to conduct the study was obtained from the local ethics committee (2-PĒK-4/528/2023), along with permission from Pauls Stradins Clinical University Hospital.

Patients who worked only in the city and those who worked on the roof of the reactor were divided into two groups depending on their duration of stay. The groups were as follows: duration of stay 1–3 months, and duration of stay 4–6 months.

Duration of stay among individuals who worked only in the city: 1–3 months – 9 individuals; 4–6 months – 8 individuals.

Duration of stay among individuals who worked on the roof of the reactor: 1–3 months – 5 individuals; 4–6 months – 3 individuals.

Among those who had worked only in the city, the types of jobs they held were as follows:

• Demolishing buildings and throwing furniture and household items from the windows

• Bus drivers evacuating inhabitants and delivering food

• Washing cars and streets

• Land work (planting wood, delivering sand, etc.)

Measurement of radiation in the city

Statistical data analysis. The assumption of data distribution was assessed using the Shapiro-Wilk test and inspection of the normal Q-Q plots. The assumption of homogeneity of variance was tested using Levene's test. The Kruskal-Wallis H test was conducted to assess differences in the actual thickness of the posterior lens cortex, the percentage of total lens thickness occupied by the posterior lens cortex, and total lens thickness between the research groups. Bonferroni correction was applied in the post hoc analysis. Statistical analyses were performed using Jamovi statistical software (https://www.jamovi.org). An alpha level of 0.05 was used for all statistical analyses.

Results

The study examined the eye health of Chornobyl cleanup workers compared with a healthy control group. The cleanup workers were further divided into two subgroups: those working in the city and those working on the roof near or inside the reactor unit.

There was no statistically significant difference in lens thickness between the healthy control group (median 4.7 mm, IQR 4.5–4.9 mm) and Chornobyl cleanup workers who worked in the city (median 4.8 mm, IQR 4.5–4.9 mm). However, the cleanup workers who worked on the roof or inside the reactor unit had significantly lower median lens thickness (4.4 mm, IQR 4.4–4.5 mm) compared with the healthy controls and city workers ($p = 0.002$).

The posterior cortex, which is a part of the lens, showed a significant difference in thickness between the groups. The healthy control group had a median posterior cortex thickness of 0.68 mm (IQR 0.58–0.85 mm, figure 1). Cleanup workers who worked in the city did not show a significant difference (median 0.68 mm, IQR 0.62–0.72 mm, figure 2) compared to the controls. However, workers who were on the roof or inside the reactor had a significantly thicker posterior cortex (median 0.82, IQR 0.69–0.89 mm) than both the healthy controls and city workers ($p = 0.002$).

The proportion of the lens occupied by the posterior cortex was also significantly different between the groups. The healthy control group had a median of 14.7% (IQR 13.0–16.5%, figure 1) of the lens occupied by the posterior cortex. Cleanup workers in the city again showed no significant difference (median 15.0%, IQR 14.5–16.2%, fig-

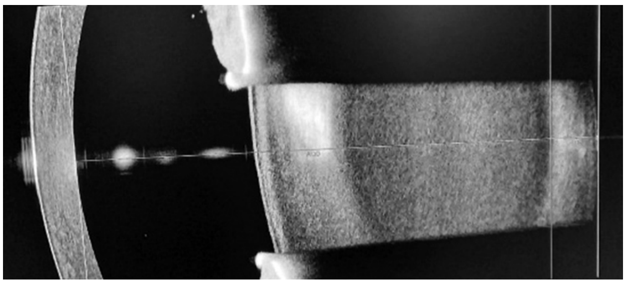

Figure 1. Posterior lens cortex thickness in a non-exposed individual.

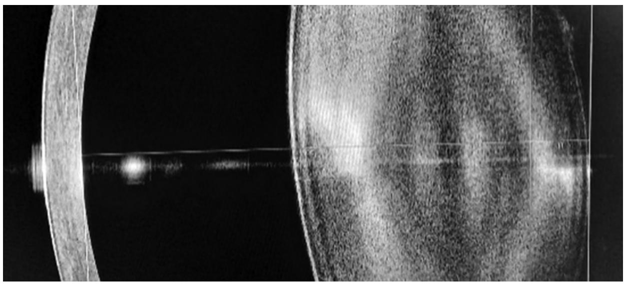

Figure 2. Posterior lens cortex thickness in a patient who had worked in Chornobyl City.

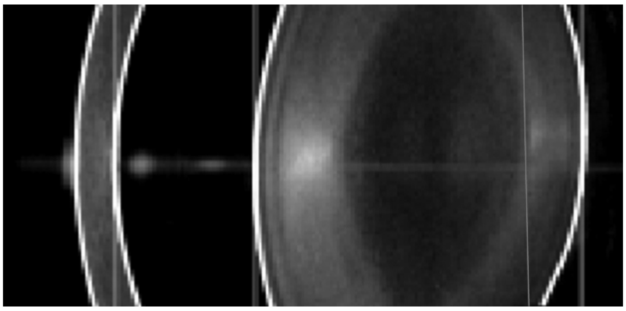

Figure 3. Posterior lens cortex thickness of a patient who had worked on the roof near the reactor.

ure 2) compared to controls. Workers on the roof or inside the reactor had a significantly higher percentage of their lens occupied by the posterior cortex (median 17.3%, IQR 15.5–18.5%) compared with both the controls and city workers ($p < 0.001$), figure 3.

The healthy controls had a median age of 67 years old (IQR 61–69 years). Overall, the cleanup workers were younger, with a median age of 63.5 years old (IQR 60–66 years) for those who worked in the city and 61 years old (IQR 59–61 years) for those who worked on the roof or inside the reactor.

Epsilon squared (Ɛ2) is a measure of effect size. The values reported in the table 1 (ranging from 0.1 to 0.15) indicate a medium effect size for the significant differences observed in lens thickness, posterior cortex thickness, and percent of posterior cortex thickness of the lens.

Information about the ocular complaints people had during their stay in the city or shortly after returning home was also collected, both from individuals who had worked only in the city and those who had worked on the roof of the reactor. Almost none of the patients had any ocular complaints. Only one person mentioned that they had itchy, red, and watery eyes during their stay in the city. There was another patient who had corneal leukoma who stated that this condition began within weeks after returning home. However, whether this was due to radiation exposure remains unclear, because this person also mentioned that during their stay, they had a corneal trauma with a piece of glass that had flown directly into that particular eye and was successfully removed.

Among the patients who had worked on the roof of the reactor, most did have complaints during their stay and shortly after returning home. However, the number of individuals who had no complaints was still very large. No ocular complaints were reported in this patient group.

Discussion

Our results indicate that exposure to increased doses of radiation can increase the risk of developing posterior cortex cataracts; the total thickness of the posterior lens cortex was significantly higher in the patient group that worked on the roof or inside the reactor compared with the non-exposed group. However, no significant difference was found between the patient group that worked only in the city and non-exposed individuals. The percentage of the lens cortex that occupied the entire lens was significantly higher in the patient group that worked on the roof or inside the reactor than in the non-exposed group. There was no significant difference between the percentage of people who worked only in the city and non-exposed individuals.

Research results prove that people who receive higher radiation doses have more significant changes in lens structure. The fact that people who worked only in the city did not show any significant change was attributed to the fact that there have been more than 30 years since the accident, and the patients who did not receive such a high radiation dose were genetically more resistant to radiation exposure. The individuals who would have shown a significant change have already passed away shortly after the accident, or perhaps their posterior cataract was so severe that cataract surgery had already been performed. It could be suggested that people who worked on the roof or inside the reactor also have a significantly thinner median total lens thickness; therefore, the percentage of the posterior cortex that is occupied is also significantly larger. However, the fact that not only the percentage but also the actual

Table 1. Eye health outcomes of Chornobyl cleanup workers according to exposure level (city vs. roof/reactor)

Parameters	Healthy people	Chornobyl ex-clean-up workers		p-value	ε^2
		In the city,	on the roof near or inside the reactor unit		
	Median (Q1-Q3)	Median (Q1-Q3)	Median (Q1-Q3)		
Lens thickness	4.7 (4.5-4.9) a	4.8 (4.5-4.9) a	4.4 (4.4-4.5) b	0.002	0.13
Posterior cortex thickness	0.68 (0.58-0.85) a	0.82 (0.69-0.89) b	0.68 (0.62-0.72) a	0.002	0.13
The percent posterior cortex occupies the entire lens	14.7 (13.0-16.5) a	17.3 (15.5-18.5) b	15.0 (14.5-16.2) a	<0.001	0.15
Age	67 (61-69) a	63.5 (60-66) ab	61 (59-61) b	0.008	0.1

Note: (Q1-Q3) - interquartile range presented as the first and third quartiles; effect size: Epsilon squared ε^2, a-b values with different superscript letters in the same row indicate significant differences ($p<0.05$).

posterior cortex thickness in the patient group who worked on the roof or inside the reactor is significantly thicker proves that this is due to increased radiation exposure.

The epsilon measure also indicated that the medium effect size for the significant differences observed in posterior cortex thickness (0.13) and percent of posterior cortex thickness of the lens (0.15) between the groups was high, indicating high statistical reliability. To improve the accuracy of the results, more patients should be assessed. The results would be relatively reliable if approximately 100 patients were included in each group.

Conclusions

In conclusion, there were significant changes and an increase in the prevalence of posterior cortex cataract among people who had worked on the roof or inside of the reactor. The proportion of the lens occupied by the posterior cortex was significantly larger in the patient group who worked on the roof near the reactor (median 17.3%, IQR 15.5–18.5%) compared with both the controls and city workers ($p < 0.001$). However, no significant difference was observed between patients who had only worked in the city and healthy, non-exposed individuals. Numerous studies have posited that heightened radiation exposure can induce substantial alterations in ocular structural integrity. Conversely, other studies have yielded results that exhibit a higher degree of uncertainty and ambiguity regarding the impact of exposure to increased radiation doses.

References

1. **Dolin PJ.** Ultraviolet radiation and cataract: a review of the epidemiological evidence. Br J Ophthalmol, 1994. 78(6): p. 478-82.
2. **Asbell PA, et al.,** Age-related cataract. Lancet. 2005; 365(9459): 599-609.
3. Löfgren S. Solar ultraviolet radiation cataract. Exp Eye Res. 2017; 156: 112-116.
4. **Hightower KR.** The role of the lens epithelium in development of UV cataract. Curr Eye Res, 1995. 14(1): p. 71-8.
5. **Michael R.** Development and repair of cataract induced by ultraviolet radiation. Ophthalmic Res. 2000; 32 Suppl 1: ii-iii; 1-44.
6. **Balasubramanian D.** Ultraviolet radiation and cataract. J Ocul Pharmacol Ther. 2000; 16(3): 285-97.
7. **Bond VP, Fishler MC, Sullivan WH**. The physician and the atomic bomb. Calif Med. 1951; 75(6): 400-7.
8. **Rehani MM, et al.** Radiation and cataract. Radiat Prot Dosimetry. 2011; 147(1-2): 300-4.
9. **Strigari L, et al.** Dose-Effects Models for Space Radiobiology: An Overview on Dose-Effect Relationships. Front Public Health. 2021; 9: 733337.
10. **Shore RE, Neriishi K, Nakashima E.** Epidemiological studies of cataract risk at low to moderate radiation doses: (not) seeing is believing. Radiat Res. 2010; 174(6): 889-94.
11. **Oosta GM, Mathewson NS.** Effect of high-power density microwave irradiation on the soluble proteins of the rabbit lens. Invest Ophthalmol Vis Sci. 1979; 18(4): 391-400.
12. **Weir JR.** Radiation damage, at high temperatures. Science. 1967; 156(3783): 1689-95.
13. **Stewart WG.** Radiation hazards control in survival operations in the event of a nuclear war. Can Med Assoc J. 1962; 87(22): 1173-7.
14. **Pickering JE, Vogel FS.** Demyelinization induced in the brains of monkeys by means of fast neutrons; pathogenesis of the lesion and comparison with the lesions of multiple sclerosis and Schilder's disease. J Exp Med. 1956; 104(3): 435-42.
15. **Waters WR**. Reduction of fallout radiation hazards in health installations. Can Med Assoc J. 1962; 87(22): 1177-83.
16. **Littlefield LG et al.** Do recorded doses overestimate true doses received by Chernobyl cleanup workers? Results of cytogenetic analyses of Estonian workers by fluorescence in situ hybridization. Radiat Res. 1998; 150(2): 237-49.
17. **Monte L et al.** Assessment of state-of-the-art models for predicting the remobilisation of radionuclides following the flooding of heavily contaminated areas: the case of Pripyat River floodplain. J Environ Radioact. 2006; 88(3): 267-88.
18. **Levin SG, Young RW, Stohler RL.** Estimation of median human lethal radiation dose computed from data on occupants of reinforced concrete structures in Nagasaki, Japan. Health Phys. 1992; 63(5): 522-31.
19. **Park MY, Jung SE.** Patient Dose Management: Focus on Practical Actions. J Korean Med Sci. 2016; 31 Suppl 1(Suppl 1): S45-54.
20. **Roberts WC.** Facts and ideas from anywhere. Proc (Bayl Univ Med Cent). 2018; 31(2): 257-267.
21. **Laćan I, McBride J, Witt D.** Urban forest condition and succession in the abandoned city of Pripyat, near Chernobyl, Ukraine. Urban Forestry & Urban Greening, 2015. 14.
22. **Likhtarev IA, Chumack VV, Repin VS.** Retrospective reconstruction of individual and collective external gamma doses of population evacuated after the Chernobyl accident. Health Phys. 1994; 66(6): 643-52.
23. **Drozdovitch V.** Radiation Exposure to the Thyroid After the Chernobyl Accident. Front Endocrinol (Lausanne). 2020; 11: 569041.
24. **Havlik E, Bergmann H, Höfer R.** [Diagnosis of radionuclide uptake using a whole body counter]. Acta Med Austriaca. 1986; 13(4-5): 99-101.
25. **Baverstock KF.** A preliminary assessment of the consequences for inhabitants of the UK of the Chernobyl accident. Int J Radiat Biol Relat Stud Phys Chem Med. 1986; 50(1): iii-xiii.
26. **Marino F, Nunziata L.** Long-Term Consequences of the Chernobyl Radioactive Fallout: An Exploration of the Aggregate Data. Milbank Q. 2018; 96(4): 814-857.
27. **Loganovsky KN et al.** Radiation-Induced Cerebro-Ophthalmic Effects in Humans. Life (Basel). 2020. 10(4).
28. **Pasyechnikova N, Fedirko P, Babenko T.** A case of radiation cataract found 29 years after radiation exposure. Oftalmologicheskii Zhurnal. 2020; 89: 61-63.
29. **Charles MW, Brown N**. Dimensions of the human eye relevant to radiation protection. Phys Med Biol. 1975; 20(2): 202-18.
30. **Ainsbury EA et al.** Radiation cataractogenesis: a review of recent studies. Radiat Res. 2009; 172(1): 1-9.
31. **Lipman RM, Tripathi BJ, Tripathi RC.** Cataracts induced by microwave and ionizing radiation. Surv Ophthalmol. 1988; 33(3): 200-10.
32. **Worgul BV et al.** Lens epithelium and radiation cataract. I. Preliminary studies. Arch Ophthalmol. 1976; 94(6): 996-9.
33. **Worgul BV et al.** UACOS - the Ukrainian/American Chernobyl ocular study. in International conference on radiation and health Program and book of abstracts. 1996. Israel.

34. **Lerebours A et al.** Evaluation of cataract formation in fish exposed to environmental radiation at Chernobyl and Fukushima. Sci Total Environ. 2023; 902: 165957.
35. **Darte JM,** Little WM Management of the acute radiation syndrome. Can Med Assoc J. 1967; 96(4): 196-9.

Information about authors and disclosure of information

Author's contribution. *E.G.: Writing, conceptualisation, investigation, data collection, reviewing and editing. Author A.Z.: Review and revision. Author I.M.: data collection, formal analysis. Author M.Z.: formal analysis and statistics. Author G.L.: conceptualisation; resources, project administration, formal review. All authors analysed the results and approved the final version of the manuscript.*

Ethics statement. *This study was conducted in compliance with the Helsinki Declaration of Human Rights and ethical principles. Permission to conduct the study was obtained from the local ethics committee (approval number 2-PĒK-4/528/2023) and from Pauls Stradins Clinical University Hospital. All study participants signed informed consent.*

Financial support. *This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.*

Conflict of interest statement. *None of the following authors have any proprietary interests or conflicts of interest related to this submission. This submission has not been published anywhere previously and is not simultaneously being considered for any other publication.*

Disclaimer. *The views expressed in this article are based on our research and do not necessarily represent the official position of our institution or funder.*

Received 15.03.2024