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MAYAK WORKER COHORT: CHARACTERISTICS AND KEY RESULTS OF EPIDEMIOLOGICAL STUDIES

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Introduction. The medical registry of workers at the Mayak Production Association (PA) was initially established with the purpose of studying the long-term stochastic health effects of occupational radiation exposure at the first nuclear industry enterprise in the USSR.
Objective. Assessment of radiogenic risk from prolonged occupational exposure among the Mayak PA worker cohort, including the subcohort of workers exposed to normal radiation conditions.
Materials and methods. This study represents one phase of a lifelong retrospective epidemiological investigation of health indicators, including the incidence and mortality from malignant neoplasms (MN), conducted within the framework of the medical-dosimetric registry of Mayak PA workers. The available study cohort is limited to employees of three main production facilities and two auxiliary plants, hired between 1948 and 1982. Within the study cohort, two subcohorts are distinguished based on factual data on radiation exposure levels and assessed medical outcomes. These include the subcohort of 1948–1958, personnel hired during the technology development phase and characterized by high occupational radiation exposure levels and that of 1959–1982, hired during routine operational periods with radiation doses comparable to modern limits. At the current stage, the attained age of workers in the second subcohort and the volume of accumulated data have enabled an analysis focused on individuals having worked under standard conditions, excluding the effects of high doses and dose rates. This has expanded the scope of statistically significant direct estimates of radiogenic MN risk. All studies of radiogenic risk in the cohort of Mayak PA workers were conducted using the Epicure statistical software package.
Results. The cohort comprised 25,755 workers. The vital status during the period of up to 31.12.2018 was known for 94% of subjects. In the 1948–1958 subcohort, the mean cumulative gamma radiation dose was 748 mGy, compared to 130 mGy in the 1959–1982 subcohort. Overall, 10,304 individuals (40.1% of the cohort) received low doses of gamma radiation. The mean cumulative lung dose from alpha radiation due to incorporated ^{239}Pu was 179.4 mGy, with 329.2 mGy and 41.0 mGy for the 1948–1958 and 1959–1982 subcohorts, respectively. The estimated excess relative risk per 1 Gy of alpha radiation lung dose was 3.5–8 for 60-year-old males. No deviations from linearity were found. Radiogenic risk decreased with an increase in age. A nonlinear dose-response relationship was identified for liver MN. The primary long-term effect of external gamma radiation was leukemia development, where a nonlinear model incorporating effect modification by age at exposure, time since exposure, and attained age provided better approximation than a linear model. For solid MN, the risk coefficient from external gamma radiation ranged 0.1–0.4 per 1 Gy. Among workers employed under normal radiation conditions (1959–1982 hiring period), the attributable risk assessment suggests that 1–5% of MN (excluding tumors in plutonium primary deposition organs) were radiation-induced, solely due to external gamma exposure.
Conclusions. The Mayak PA worker cohort, with its high-quality medical and dosimetric data, serves as a crucial source for direct epidemiological assessments of radiogenic risks from prolonged occupational radiation exposure. The identification of the routine production operation period not only validates the magnitude of carcinogenic risk but also highlights the need to extend both the follow-up period and the cohort itself to include more workers exposed to conditions comparable to modern standards.

Keywords: personnel; exposure; radiogenic risk; malignant neoplasms; non-tumor diseases; regulation; radiation safety

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Compliance with ethical principles: no bioethics committee approval was required as the study was based on archival data.

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КОГОРТА РАБОТНИКОВ ПО «МАЯК»: ХАРАКТЕРИСТИКА И ОСНОВНЫЕ РЕЗУЛЬТАТЫ ЭПИДЕМИОЛОГИЧЕСКИХ ИССЛЕДОВАНИЙ

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Введение. Регистр персонала ПО «Маяк» создан для исследования отдаленных стохастических медицинских последствий профессионального радиационного облучения работников первого в СССР предприятия ядерной промышленности.

Цель. Оценка радиогенного риска при пролонгированном профессиональном облучении в когорте работников ПО «Маяк», в том числе в когорте лиц, работавших в условиях штатной радиационной обстановки.

Материалы и методы. Выполненная работа является одним из этапов пожизненного ретроспективного эпидемиологического исследования показателей здоровья, в том числе заболеваемости и смертности от злокачественных новообразований (ЗНО), проводимого на базе медико-дозиметрического регистра работников ПО «Маяк». Доступная для исследованная когорта ограничена работниками трех основных производств и двух вспомогательных заводов, а также периодом найма на работу 1948–1982 гг. В исследуемой когорте, основываясь на фактических данных об уровнях облучения и полученных оценках медицинских последствий, выделены две субкогорты: 1948–1958 гг. — субкогорта найма в период освоения технологии и высоких уровней профессионального облучения и 1959–1982 гг. — субкогорта найма в период штатной эксплуатации производства и сопоставимых с современными пределами доз. На современном этапе достигнутый возраст работников, включенных во вторую субкогорту, и объем накопленных данных позволил провести анализ для лиц, работавших в штатных условиях, исключив влияние высоких доз и мощностей доз, и расширить область полученных статистически значимых прямых оценок радиогенного риска ЗНО. Все исследования радиогенного риска в когорте работников ПО «Маяк» проведены с использованием пакета для статистической обработки данных Epicure.

Результаты. Когорта состоит из 25 755 работников. Жизненный статус в период до 31.12.2018 известен для 94%. В субкогорте 1948–1958 гг. найма средняя накопленная доза гамма-облучения составила 748 мГр, 1959–1982 гг. — 130 мГр. В целом область малых доз гамма-излучения включала 10 304 (40,1% членов когорты) человека. Средняя накопленная доза в легких за счет альфа-облучения инкорпорированным ^{239}Pu составляла 179,4 мГр, для субкогорт 1948–1958 и 1959–1982 гг. — 329,2 и 41,0 мГр соответственно. Оценка избыточного относительного радиационного риска на 1 Гр дозы альфа-излучения в легких составила 3,5–8,0 на 1 Гр для мужчин в возрасте 60 лет. Не найдено отклонений от линейности. Радиогенный риск снижался с увеличением возраста. Выявлена нелинейная зависимость риска ЗНО печени. Основным отдаленным эффектом внешнего гамма-облучения являлось развитие лейкоза, для которого нелинейная зависимость с модификацией радиационного риска по временным характеристикам, связанным с возрастом на момент облучения, временем, прошедшим с момента облучения, и достигнутым возрастом является лучшей аппроксимацией, чем линейная. Для солидных ЗНО коэффициент риска от внешнего гамма-излучения составил 0,1–0,4 на 1 Гр. Среди лиц, работавших в условиях штатной радиационной обстановки (1959–1982 гг. найма), оценка атрибутивного риска ЗНО, за исключением опухолей органов основного депонирования плутония, позволяет отнести 1–5% случаев к радиационно-индуцированным, причем только вследствие влияния внешнего гамма-излучения.

Выводы. Когорта работников ПО «Маяк», обеспеченная высококачественными медико-дозиметрическими данными, является важным источником прямых эпидемиологических оценок радиогенного риска при профессиональном пролонгированном радиационном воздействии. Выделение периода штатной эксплуатации производства, с одной стороны, подтверждает величину канцерогенного риска, с другой — указывает на необходимость расширения периода наблюдения и самой когорты лиц, работавших в условиях, сопоставимых с современными.

Ключевые слова: персонал; облучение; радиогенный риск; злокачественные новообразования; неопухолевые заболевания; нормирование; радиационная безопасность

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Соответствие принципам этики: одобрение биоэтического комитета не требовалось, поскольку исследование выполнено на основе архивной информации.

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INTRODUCTION

Hygienic regulation of ionizing radiation is based on understanding its medical consequences. For this reason, since the first years of practical use of ionizing radiation, permissible exposure levels have decreased by more than an order of magnitude: from 500 mSv per year in the 1930s to 20 mSv per year today[1]. The primary reason for this gradual reduction in dose limits is related to the stochastic (carcinogenic) nature of the main adverse effects of ionizing radiation, which typically develop following long latency periods. To assess the risks associated with these effects, prolonged (and still ongoing) observation of irradiated populations is required—currently spanning a maximum of 70–75 years. During this period, methods for radiation-epidemiological studies have been developed, and estimates of radiogenic risk have been

[1] Romanovich IK, Balonov MI, Barkovsky AN, Brook GYa, Vishnyakova NM, Golikov VYu, et al. Comments on the Radiation Safety Standards (RSS-99/2009). Edited by Academician of the Russian Academy of Medical Sciences Onishchenko GG. St. Petersburg: Professor P.V. Ramzaev St. Petersburg Research Institute of Radiation Hygiene; 2012. EDN: YKYHSP

obtained (through epidemiological and radiobiological research)[2].

The selection, quality assessment, and evaluation of scientific research results are conducted by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Based on continuously updated data on the relationship between cancer incidence, mortality, and ionizing radiation doses, UNSCEAR systematically publishes scientific reports on the levels and consequences of radiation exposure to human health and the environment. These reports are recognized as a reliable and comprehensive source of information by the international community and are widely used for risk assessment and radiation protection measures. Radiation safety recommendations are formulated by the International Commission on Radiological Protection (ICRP). In the USSR and later in the Russian Federation, occupational dose limits for radiation workers have always aligned with ICRP guidelines [1].

The Life Span Study (LSS) of atomic bomb survivors in Hiroshima and Nagasaki (Japan) remains the primary source of quantitative radiogenic risk estimates, due to its large cohort size (over 100,000 subjects) and wide range of radiation doses (up to 4 Gy) [2]. The cohort includes both males and females of various ages at exposure (from children to the elderly), enabling robust population risk assessments[3]. In its latest Publication 103, providing recommendations for the radiological protection of workers and the public, the ICRP states:

"Risk modeling was based on data from the LSS cohort of Japanese atomic bomb survivors, but epidemiological literature was also reviewed to compare other studies with LSS-derived estimates."[4]

Thus, from a radiation safety perspective, the scientific community requires validation of LSS findings using data on the effects of occupational exposure among workers in radiation-hazardous industries.

The Mayak Production Association (PA) was the first nuclear industry enterprise in the USSR. The Mayak PA Personnel Registry was created as part of the Epidemiology Department to study long-term stochastic effects of occupational ionizing radiation exposure. Data collection began in the mid-1980s and continues up to the present [3].

The cohort derived from this registry differs from other similar cohorts [4–6], remaining the only global cohort demonstrating statistically significant effects from both alpha radiation (via incorporated plutonium) and external gamma exposure[5].

In this research, we aim to assess radiogenic risks from prolonged occupational radiation exposure in the Mayak PA worker cohort, including the subcohort employed under normal radiation conditions.

MATERIALS AND METHODS

Inclusion criteria for the study cohort and subgroup stratification

A long-term retrospective epidemiological study on the incidence and mortality from malignant neoplasms (MN) was conducted using the medical-dosimetric registry of Mayak Production Association (PA) workers. Initially, the Mayak PA registry contained information exclusively on personnel working during the 1948–1972 period at three main production facilities (reactors, radiochemical and chemical-metallurgical plants) [7]. Subsequently, the registry was extended to include data on workers hired during the following decade [8], as well as those from two auxiliary facilities, i.e., the water treatment plant and the mechanical repair plant. The registry continues to be updated both by adding newly hired workers at these facilities, currently including individuals employed up to 2016 [3], and by collecting data on employees from other departments. As of today, the Mayak PA medical-dosimetric registry covers the data on workers employed at the main plants and other enterprise divisions in 1948–2016.

The Mayak worker cohort, which is currently available for study, is limited to workers from three main and two auxiliary production facilities hired in 1948–1982. This restriction is related to insufficient and lower-quality dosimetric monitoring of personnel from other Mayak PA departments, particularly regarding internal exposure from incorporated radionuclides.

At the time of commissioning the Mayak PA, knowledge about the effects of radiation on the human body was limited. The delayed manifestation of health consequences also contributed to a lag in implementing more stringent radiation exposure limits. In the USSR, radiation safety standards were based on ICRP recommendations. The authors in [9] provide detailed information on the evolution of dose limits for radiation workers — from initial levels of 0.1 R/day and 30 R/year to the annual limit of 50 mSv recommended by the ICRP[6] and implemented through Regulation No. 333-60[7].

The Mayak PA personnel registry initially identified four subcohorts based on the year of employment at the main production facilities: 1948–1953, 1954–1958, 1959–1963, and 1964–1972 [10, 11]. Subsequently, the fifth subcohort (1973–1982) and workers from two auxiliary facilities were added [8]. Currently, based on actual radiation exposure levels and assessed health outcomes, two subcohorts have been distinguished:

- the 1948–1958 subcohort includes workers hired during the technology development phase with high occupational radiation exposures;

[2] ICRP Publication 103. Recommendations of the ICRP. Annals of the ICRP; 2008. https://doi.org/10.1016/j.icrp.2007.10.003
[3] ICRP Publication 26. ICRP. Recommendations of the ICRP. Ann. ICRP; 1977.
[4] ICRP Publication 103. Recommendations of the ICRP. Ann. ICRP; 2008. https://doi.org/10.1016/j.icrp.2007.10.003
[5] ICRP Publication 150. Cancer risk from exposure to plutonium and uranium. Ann. ICRP; 2021. https://doi.org/10.1177/01466453211028020
[6] ICRP. Publication 1. Recommendations of the International Commission on Radiological Protection. Pergamon Press, Oxford; 1977.
[7] Sanitary Regulations for Work with Radioactive Substances and Sources of Ionizing Radiation No. 333-60, approved by the Chief State Sanitary Physician of the USSR on 25.06.1960.

- the 1959–1982 subcohort includes workers hired during routine operations with exposure levels comparable to modern dose limits [8, 12].

All radiogenic risk studies in the Mayak worker cohort have employed methodologies and software tools, particularly the Epicure[8] statistical software package [13], consistent with those used in both the LSS cohort and other radiation worker cohorts worldwide. Tabulated data are presented with quantitative characteristics including median (M_e), minimum (min), and maximum (max) values.

RESULTS AND DISCUSSION

Cohort size and follow-up period

Table 1 presents the cohort and subcohort sizes along with the distribution of workers by sex, birth year, age at hiring, and employment duration. The cohort comprised 25,755 workers, including 25% females, with a wide range of birth years (1886–1965) and ages at employment initiation (18–69 years). The 1948–1958 hiring subcohort included 13,790 workers (53.5%), while the 1959–1982 subcohort contained 11,966 (46.5%). Due to sufficient availability of male specialists, females constituted only 20.7% in the latter subcohort, compared to 28.2% in the early post-war years. Most workers had already completed their employment at the enterprise — by 2018, 98% of workers had been discharged, including 100% from the first subcohort.

Information on the vital status of cohort members (specifically the year of departure from the city, location, death data) was collected and prepared for use in epidemiological studies through 2018 inclusive (Table 2). The vital status is known for 24,146 individuals (93.8%). Among those with the known vital status, 17,810 persons (73.8%) had died, with 89.0% deceased in the first decade of hire subcohort and 57.1% in the 1959–1982 hire subcohort. The increase in deaths in recent years (2009–2018) was substantial (23.3% of total deaths over the 70-year observation period). Extending the observation period through 31.12.2018 allowed accumulation of over 1 million person-years of follow-up for analysis of radiogenic mortality risk.

Cause-of-death and cancer incidence data

Cause of death was coded according to two International Statistical Classifications of Diseases[9] and Related Health Problems, 9th and 10th revisions (ICD-9, ICD-10). Both codes are provided for each worker.

For all individuals who died in the city, information on the cause of death was obtained from medical sources or civil registry records. Due to the availability of medical information among those who died in the city, the proportion of unknown causes of death is 1.6% for the entire observation period and 2.7% for 2010–2018.

For individuals who left the city, obtaining information on the cause of death from official sources is currently virtually impossible. However, even before the adoption of the Federal Law “On Personal Data,”[10] this was a challenging task. As a result, among those who left and died before the 2000s, the number of individuals with an unknown cause of death was ≈7%, while later—on average, about 50% (Fig.). Over the past 20 years, the primary source of data on the cause of death has remained personal contact with relatives.

The structure of causes of death differed slightly depending on the hiring period. On average, 47.8% of deaths were due to cardiovascular diseases, 24.3% to malignant neoplasms (MN), and 13.1% to external causes (Table 3).

Unlike mortality data, which were obtained for all members of the study cohort regardless of their place of residence, information on diseases is currently available only for the period when individuals resided in Ozersk. All cases were coded according to ICD-9 and ICD-10. Additionally, the data included morphological diagnoses of MN in accordance with the International Classification of Diseases for Oncology (ICD-O)[11].

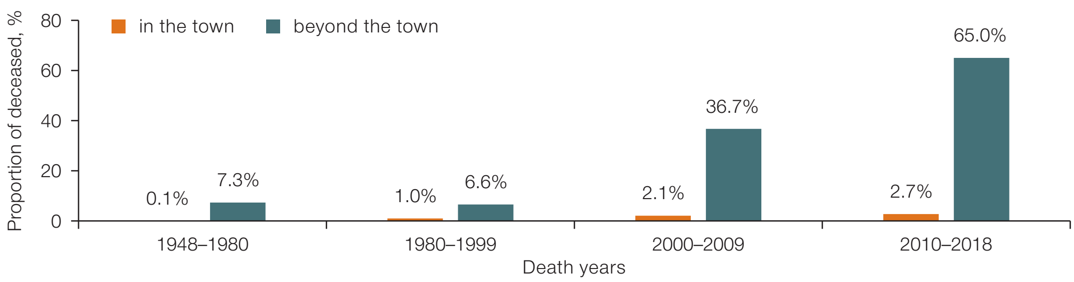

Figure prepared by the authors using data from the Mayak Production Association Personnel Registry

Fig. Proportion with unknown cause of death

[8] Preston DL, Lubin J, Pierce DA, McConney ME, Shilnikova NS. Epicure Manuals.URL: https://hirosoft.com/wp-content/uploads/nethelp/NetHelp/index.html#!Documents/userguide.htm (access date: 06.05.2025).
[9] International Classification of Diseases and Related Health Problems) ICD-10 Version:2019
[10] Federal Law No. 152-FZ of 27.07.2006 «On Personal Data».
[11] International Classification of Diseases for Oncology (ICD-O), 3rd ed., 1st revision. St. Petersburg: «Problems in oncology», 2017.

Table 1. **Quantitative composition of the Mayak PA worker cohort**

Numerical Profile	Hiring period		
	1948–1958	1959–1982	1948–1982
Number of workers, *n*	13 790	11 965	25 755
males	9907	9486	19 393
females	3883 (28.2%)	2479 (20.1%)	6362
Birth cohort			
before 1930	8080	1004	9084
1930–1950	5710	6867	12577
1950–1965	–	4094	4094
birth year range M_e (min–max)	1928 (1886–1942)	1944 (1893–1965)	1935 (1886–1965)
Age at hiring at Mayak PA, years			
<20	4369	5462	9831
20–30	7163	4372	11535
30–55	2243	2107	4350
55>	15	24	39
Age range M_e (min–max)	22.4 (14–65)	20.8 (14–69)	21.8 (14–69)
Duration of employment at Mayak PA, years			
<5	3624	2730	6354
5–20	5121	3571	8692
20–40	4001	4144	8145
40<	1044	1520	2564
employment duration (M_e)	11	18	14
Employment status			
dismissed	13 790	11 511	25 301
continue to work as of 2018	0	454	454

Table compiled by the authors using data from the Mayak PA Personnel Registry

A total of 4285 malignant neoplasm cases were diagnosed among 3805 workers in 1948–2018. Over the last 19 years of observation (2000–2018), the number of MN cases accounted for 49.2% (2107 cases)—nearly the same as during the previous 52 years (1948–1999; 2178 cases).

Dosimetric data

Dosimetric information represents fundamental data for epidemiological studies of radiogenic risk. Therefore, alongside cohort member identification, continuous updates of individual vital status data, and records of diagnosed diseases, in the 1990s, research began to revise and reconstruct absorbed doses (hereinafter referred to as doses) in specific organs from both external and internal exposure. As a result, five generations of dosimetric systems for external exposure dose assessments were sequentially developed (Doses-1999, Doses-2000, Doses-2005, Doses-2008, and Doses-2013), as well as seven generations for assessments of ^{239}Pu body content and corresponding internal exposure doses (Doses-1999, Doses-2000, Doses-2005, Doses-2008, Doses-2013, Doses-2016, and Doses-2019) [14–21].

Table 2. **Vital status in the Mayak PA worker cohort (follow-up through 31.12.2018)**

Numerical Profile	Hiring period						
	1948–1958		1959–1982		1948–1982		
	in the town	beyond the town	in the town	beyond the town	in the town	beyond the town	Total
Number of workers, *n*	6478	7311	8530	3436	15 008	10 747	25 755
traceable individuals:	6478	6148	8530	2990	15 008	9138	24 146
alive	693	696	3915	1032	4608	1728	6336
died	5785	5452	4615	1958	10 400	7410	17 810
lost to follow-up (abroad) (abroad)	0	1163 (131)	0	446 (146)	0	1609 (277)	1609
M_e of survival age, years	72.0	69.7	65.0	64.1	67.5	67.6	67.6
M_e of follow-up duration, years	45.8	44.8	40.9	41.5	42.3	43.4	42.5
Person-years of follow-up	285 621	298 546	338 662	134 088	624 283	432 634	1 056 917
Person-years of urban residence	348 938		369 600		718 538		

Table compiled by the authors using data from the Mayak PA Personnel Registry

Since the launch of the first industrial reactor at Mayak PA in 1948, the enterprise personnel have been provided with individual dosimeters for measuring gamma radiation doses [14–16]. Starting from 1984, systematic measurements of the neutron dose component have been introduced. Among the study cohort members, dosimetric data on external exposure is available for all 25,755 workers (100%), with 80% of annual dose estimates based on individual dosimeter readings. About 29% of cohort members have at least one annual dose estimated using only indirect data. For 2063 workers (8.0%), the analysis of professional employment records confirmed the absence of occupational external exposure.

The sets of annual external exposure dose values in different generations of dosimetric systems differ primarily in the list of organs for which doses were assessed and the size of the cohort. In 1949–1958, the average annual gamma radiation doses for personnel (Doses-2013, individual dose equivalent — γHp10) exceeded 50 mSv, decreasing to 5–10 mSv in 1968–1989. Since 1990, the average annual dose has not exceeded 5 mSv. Overall, 10,304 individuals (40.1% of the cohort) received low doses. The mean cumulative gamma dose was 748 mGy for the 1948–1958 hire subcohort and 130 mGy for the 1959–1982 subcohort.

Annual gamma doses were estimated through 2007. Due to the cessation of participation of Mayak PA specialists in joint studies, access to external dose data from 2008 onward has been restricted.

An analysis of autopsy materials from cohort workers revealed that internal exposure in the Mayak PA cohort essentially involved dosimetry of inhaled ^{239}Pu, compared to doses from uranium fission products, which were orders of magnitude lower [17, 18]. Estimates of nuclide content and organ/tissue doses are based on urinary ^{239}Pu activity measurements [19–21]. The latest Dose-2019 system includes dose estimates for 17 organs/tissues and lung compartments for 8395 workers. Cumulative doses varied significantly between primary plutonium deposition organs and systemic pool organs, with maximum values in bone surfaces and minimum values in stomach, intestines, and muscles.

The mean cumulative lung dose was 179.4 mGy (329.2 mGy for the 1948–1958 hiring period; 41.0 mGy for the 1959–1982 hiring period). In the first subcohort, 1394 workers (34.6%) received >100 mGy lung doses, compared to only 9.2% in the second subcohort. Conversely, 264 workers (6.5%) hired before 1959 and 1734 (39.7%) hired later received <5 mGy lung doses. Systemic organ doses were two orders lower: the mean stomach dose was 1.2 mGy, with >5 mGy doses found in 4.7% of examined workers (only 13 in the later subcohort).

Only 32.6% of workers in the study cohort underwent examination. As of 2018, approximately 2000 local residents remained available for testing, including < 200 early hires (first decade). For unexamined workers, doses were estimated using the Job Exposure Matrix (JEM) approach, covering 25,423 workers (98.7%).

The Mayak PA worker cohort remains the world's primary source on health effects of occupational plutonium exposure. The main stochastic effect of inhaled plutonium compounds is lung cancer. Numerous Mayak

Table 3. **Structure of causes of death and malignant neoplasm incidence among Mayak PA workers (follow-up through 31.12.2018)**

Cause of death / disease	Mortality, %	MN Incidence◆, %
Cause of death is known	15 767–100	–
Malignant neoplasms*	3837–24.3	4285–100
solid MN▲	3615–94.2	4056–94.7
stomach cancer∴	563–15.6	455–11.2
MN of colon, rectosigmoid junction and rectum	425–11.8	529–13.0
cancer of liver and intrahepatic bile ducts ∴	114–3.2	76–1.9
pancreatic cancer ∴	179–5.0	148–3.6
lung cancer ∴	1021–28.2	720–17.8
non-melanoma skin cancer ∴	18–0.5	571–14.1
breast cancer □	130–15.0	180–15.3
MN of female genital organs □	101–11.7	157–13.4
prostate cancer ■	147–4.9	266–8.6
bladder cancer ∴	83–2.3	268–6.6
cancer of the kidneys, other and unspecified urinary organs ∴	105–2.9	161–4
unknown primary tumor ∴	151–4.2	40–1
hemoblastoses ▲	222–5.8	229–5.3
leukemias ∴	129–58.1	114–49.8
Diseases of the blood and blood-forming organs*	20–0.1	–
Diseases of the circulatory system*	7538–47.8	–
ischemic heart disease#	4067–54.0	–
cerebrovascular diseases#	2510–33.3	–
External causes*	2061–13.1	–
Other causes*	2311–14.7	–

Table compiled by the authors using data from the Mayak PA Personnel Registry

Note: * — % of known causes of death; ▲ — % of malignant neoplasms (NM); ∴ — % of solid NM; # — % of circulatory system diseases; □ — % of NM in women; ■ — % of NM in men; ◆ — incidence data reflect diagnoses made exclusively within the Ozersk population; "–" — cases of benign or non-neoplastic nature fall outside the scope of this registry.

studies employing various dosimetric systems, observation periods, and non-radiation factors have established lung cancer dose-response models and statistically significant risk estimates [22–24].

The estimated excess relative radiation risk (ERR) per 1 Gy dose to the lungs was 3.5–8 per 1 Gy for males aged 60 years. No deviations from linear dose-response relationships were found. Radiogenic risk values showed a stronger dependence on smoking status than on gender, although these factors demonstrated moderate correlation (r = 0.61) in the Mayak PA worker cohort. Additionally, the excess risk showed a statistically significant decline with an increase in age.

Studies of the Mayak PA cohort also revealed dose-dependent relationships between alpha radiation dose and MNs in other primary plutonium deposition organs (liver, bones). For liver cancer, a nonlinear dose response was observed, although apparently being driven exclusively by high-dose exposures.

For other solid tumors as well as lymphohematopoietic malignancies, neither incidence nor mortality outcomes showed demonstrable effects from incorporated plutonium exposure levels.

Beyond plutonium-related effects, the Mayak worker cohort has provided estimates of radiogenic cancer risks from external gamma exposure. The principal late effect of gamma radiation in this cohort was leukemia development. The radiation risk for leukemia (excluding chronic lymphocytic leukemia) was approximately 3 per 1 Gy dose to red bone marrow under a linear model [25–27]. However, the data were statistically significantly better described by nonlinear (purely quadratic or linear-quadratic) models incorporating effect modification by:

- age at exposure,
- time since exposure,
- attained age [26, 27].

For solid MN, the coefficient of excess relative risk per Gy (ERR/Gy) from external gamma radiation ranged 0.1–0.4 per Gy across various studies [28–30]. When examining the influence of non-radiation factors (sex, smoking, type of production, attained age, age at hire) as modifiers of radiogenic risk, no statistically significant differences were found.

When developing models to predict MN risk among workers at modern facilities, it is important to consider the significant difference between the current working conditions, including dose loads, and those during the formative period [31–40]. The assessment of radiogenic risk for solid MN incidence (excluding MN in primary plutonium deposition organs) in relation to combined occupational gamma and alpha radiation levels among workers employed under normal radiation conditions (1959–1982 hiring period) revealed an increase in MN incidence at external radiation doses of 0.5–1.0 Gy (relative risk RR = 0.15; 95% CI: -0.21–0.51) and at alpha radiation doses up to 0.005 Gy (RR = 0.30; 95% CI: 0.07–0.53). The linear coefficient of radiation risk for MN incidence (ERR/Gy) depending on gamma radiation dose was statistically significantly different from zero only at the 90% level (0.36; 95% CI: -0.02–0.85; 90% CI: 0.03–0.76) when alpha radiation dose was not accounted for [41]. Estimates of the linear ERR/Gy coefficient for alpha radiation dose were negative[12].

In the study of cancer mortality using a linear dose-response function, the excess risk coefficient was zero for alpha radiation dose and positive, although not statistically significant, for gamma radiation dose (ERR: 0.17/Gy; 95% CI: -0.24–0.68)[13]. When conducting an interval dose estimation, a positive and statistically significant excess risk was observed only in the high-dose range of external radiation above 0.5 Gy (ERR: 0.33/Gy; 95% CI: 0–0.82). When modeling only alpha dose intervals, a statistically significant positive association was found in the dose range up to 0.005 Gy; however, this excess risk was not confirmed when using a model accounting for both radiation types [42].

Thus, among workers employed under normal radiation conditions (1959–1982 hiring period), the attributable risk assessment for MNs (excluding tumors in primary plutonium deposition organs) suggests that only 1–5% of cases can be considered radiation-induced, and solely due to external gamma radiation exposure.

In the analysis of non-cancer mortality rates among workers hired in 1959–1982[14], a comparison of various excess relative risk models based on external radiation exposure levels, both with and without consideration of internal exposure levels, showed no increase in mortality with an increase in radiation exposure. Indeed, no disease category showed a positive estimate of the ERR/Gy coefficient when using a linear dose-response relationship, nor was there a monotonic statistically significant increase in relative risk when using a nonparametric dose-response relationship.

The improvement in data approximation quality when using dose intervals was statistically significant at the 90% level only for the group of infectious and parasitic diseases: however, this was solely due to a positive estimate of excess risk in the dose interval up to 100 mGy (ERR = 0.6; 90% CI: 0.04–1.58). For the most representative category of circulatory system diseases, no dose-effect relationship was observed as well, with the only positive estimate of excess risk obtained for doses exceeding 0.5 Gy (ERR = 0.05; $p > 0.5$).

CONCLUSION

The Mayak Production Association Personnel Registry constitutes an authoritative source for epidemiological assessments of radiogenic risks associated with prolonged occupational radiation exposure at nuclear industrial facilities. Based on the worker cohort hired in 1948–1982, direct estimates of carcinogenic risk have been obtained for both external radiation doses and ^{239}Pu intake. The observation of workers who began employment during 1959–1982 serves dual purposes. On the one hand, this allows the magnitude of dose-dependent carcinogenic risk from cumulative gamma radiation exposure to be assessed. On the other hand, this work highlights the need to extend both the observation period and the cohort itself to include personnel working under exposure conditions comparable to contemporary standards.

[12] Indicators and Risk Prognosis for Long-Term Medical Consequences of Prolonged Exposure to Ionizing Radiation from External and Incorporated Sources Among Personnel at the Nuclear Industry Enterprise 'Mayak' PA Under Normal Operating Conditions, and Assessment of Medical-Demographic Health Indicators of the Population Living Near the Radiation-Hazardous Facility. Research Report (Interim). Federal State Budgetary Scientific Institution 'South Urals Institute of Biophysics', Head: Sokolnikov ME. Ozersk: 2023. State Research Registration No. 122041300044-3. Deposited at CITIS 07.02.2025, No. IKRBS I224120300119-7 / 225020709083-0.

[13] Ibid.

[14] Ibid.

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