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Dedicated to our great teachers: A.K. Gus'kova, L.A. Il'in, P.V. Ramzaev, and A.F. Tsyb

MEDICAL AND BIOLOGICAL IMPACTS OF CHERNOBYL NPP ACCIDENT (1986–2026)

Veronika I. Skvortsova[1], Andrey D. Kaprin[2], Ivan K. Romanovich[3], Igor V. Borisevich[1], Sergey A. Ivanov[2], Yury D. Udalov[4], Igor A. Berzin[1], Andrey A. Akleyev[5,6], Yulia R. Akhmadullina[6,7], Evgenia A. Blinova[6,7], Anzhelika A. Bratilova[3], Andrey Yu. Bushmanov[4], Irina A. Galstyan[4], Viktor K. Ivanov[2], Mikhail V. Konchalovsky[4], Olga S. Kravtsova[3], Irina S. Kuznetsova[6], Marat A. Maksyutov[2], Nelya A. Metlyayeva[4], Svetlana F. Sosnina[6], Yulia V. Tsareva[6], Sergey Yu. Chekin[2], Sergey M. Shinkarev[4], Olga V. Shcherbatykh[4], Lubov' A. Yunanova[4], Alexander V. Akleyev[6,7]✉

[1] Federal Medical Biological Agency, Moscow, Russia
[2] A. Tsyb Medical Radiological Research Centre — branch of the National Medical Research Radiological Centre, Obninsk, Russia
[3] Saint-Petersburg Research Institute of Radiation Hygiene after Professor P.V. Ramzaev, Saint-Petersburg, Russia
[4] State Research Center — Burnazyan Federal Medical Biophysical Center of Federal Biological Agency, Moscow, Russia
[5] South Ural State Medical University, Chelyabinsk, Russia
[6] Southern Urals Federal Research and Clinical Center for Medical Biophysics, Ozersk, Russia
[7] Chelyabinsk State University, Chelyabinsk, Russia

The paper presents the results of a 40-year follow-up of the health status of people exposed due to radiation accident at Chernobyl Nuclear Power Plant (NPP). The issues of radiation hygienic and medical monitoring implementation following Chernobyl NPP disaster in the Russian Federation are considered. Findings of the assessment of deterministic effects, including the lethal ones, in Chernobyl NPP personnel who were affected by high-dose acute external exposure in the first days after the accident are discussed together with the treatment modalities of acute radiation syndrome and its outcomes. Another subject of radiobiological and epidemiological study is long-term cancer and non-cancer effects in nuclear disaster clean-up workers who took part in emergency and recovery operations in 1986–1990 and in residents of the radioactively contaminated territories who were affected by long-term combined (external and internal) radiation exposure at a wide dose range. Health effects for the exposed population offspring, including in utero exposed individuals, are considered separately.

Keywords: Chernobyl NPP; accident; cleanup workers; population, acute radiation syndrome; radiation risk; long-term effects; biomarkers

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✉ Alexander A. Akleyev akleyev@urcrm.ru

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П.В. Рамзаеву и А.Ф. Цыбу***

МЕДИКО-БИОЛОГИЧЕСКИЕ ПОСЛЕДСТВИЯ АВАРИИ НА ЧЕРНОБЫЛЬСКОЙ АЭС (1986–2026)

В.И. Скворцова[1], А.Д. Каприн[2], И.К. Романович[3], И.В. Борисевич[1], С.А. Иванов[2], Ю.Д. Удалов[4], И.А. Берзин[1], А.А. Аклеев[5,6], Ю.Р. Ахмадуллина[6,7], Е.А. Блинова[6,7], А.А. Братилова[3], А.Ю. Бушманов[4], И.А. Галстян[4], В.К. Иванов[2], М.В. Кончаловский[4], О.С. Кравцова[3], И.С. Кузнецова[6], М.А. Максютов[2], Н.А. Метляева[4], С.Ф. Соснина[6], Ю.В. Царева[6], С.Ю. Чекин[2], С.М. Шинкарев[4], О.В. Щербатых[4], Л.А. Юнанова[4], А.В. Аклеев[6,7]✉

[1] Федеральное медико-биологическое агентство, Москва, Россия
[2] Медицинский радиологический научный центр им. А.Ф. Цыба — филиал ФГБУ «Национальный медицинский исследовательский центр радиологии», Обнинск, Россия
[3] Санкт-Петербургский научно-исследовательский институт радиационной гигиены им. профессора П.В. Рамзаева, Санкт-Петербург, Россия
[4] Государственный научный центр Российской Федерации — Федеральный медицинский биофизический центр им. А.И. Бурназяна, Москва, Россия
[5] Южно-Уральский государственный медицинский университет, Челябинск, Россия
[6] Южно-Уральский федеральный научно-клинический центр медицинской биофизики Федерального медико-биологического агентства, Озерск, Россия
[7] Челябинский государственный университет, Челябинск, Россия

В работе представлены результаты сорокалетних наблюдений за состоянием здоровья людей, подвергшихся радиационному воздействию вследствие аварии на Чернобыльской АЭС. Рассмотрены проблемы организации радиационно-гигиенического и медицинского мониторинга после аварии на территории Российской Федерации. Представлены данные по оценке детерминированных эффектов у аварийных работников АЭС, которые подверглись в первые дни после аварии острому внешнему облучению в высоких дозах, включая летальные; методы лечения острой лучевой болезни и ее исходы. Предметом радиобиологического и эпидемиологического рассмотрения в статье также являются отдаленные канцерогенные и нераковые эффекты у ликвидаторов последствий аварии, участвовавших в аварийно-восстановительных работах в 1986–1990 гг., а также у населения, проживающего на радиоактивно загрязненных территориях, которые подверглись длительному сочетанному (внешнему и внутреннему) радиационному воздействию в широком диапазоне доз. Отдельно рассматриваются последствия аварии для здоровья потомков облученных людей, включая внутриутробно облученных.

Ключевые слова: Чернобыльская АЭС; авария; ликвидаторы; население; острая лучевая болезнь; радиационный риск; отдаленные эффекты; биомаркеры

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✉ Аклеев Александр Васильевич akleyev@urcrm.ru

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INTRODUCTION

The Chernobyl nuclear power plant (NPP) accident, which occurred 40 years ago, was not only the source of the largest uncontrolled release of radioactive substances into the environment in history, but also the most extensive project to mitigate its consequences. More than 500,000 military personnel and workers of various specialties and agencies of the USSR took part in this effort. Following the accident, the state implemented extraordinary measures — first, to address the immediate consequences of the disaster, and later, to provide medical-social protection and rehabilitation for the irradiated population. After the adoption of Federal Law No. 1244-1 of 1991 “On the Social Protection of Citizens Exposed to Radiation as a Result of the Chernobyl Nuclear Disaster”[1], cleanup workers of 1986–1990 and their children born after the accident, as well as residents of radioactively contaminated territories (RCTs), were guaranteed free medical care and mandatory lifelong special medical monitoring. Under this law, irradiated individuals gained the right to

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[1] Law of the Russian Federation No. 1244-1 of May 15, 1991 “On Social Protection of Citizens Exposed to Radiation as a Result of the Catastrophe at the Chernobyl Nuclear Power Plant”.

compensation for damage caused to their health and benefits for the increased risk of developing adverse health effects.

Within the framework of several state and federal targeted programs, scientific research and medico-hygienic measures were carried out to rehabilitate irradiated individuals and RCTs, aimed at improving the health, quality of life, and living conditions of the exposed population. After the accident, experts predicted numerous and highly diverse health consequences for the irradiated population. The forty years that have passed since the accident now allow us to summarize the results of long-term medical observations of irradiated individuals and their descendants, and to draw conclusions about the medico-biological consequences of this tragedy.

The results of medical follow-up of individuals exposed due to the accident and the studies conducted represent significant scientific potential, which enables obtaining fundamentally new knowledge about radiation effects in humans and the mechanisms of their development. The analysis of medico-biological effects was carried out for three human radiation exposure scenarios:

- acute total external exposure at high doses, to which emergency workers at the Chernobyl NPP were subjected on the night of April 26, 1986.
- prolonged, predominantly external exposure at low and intermediate doses, experienced by the accident cleanup workers of 1986–1990.
- chronic combined (external and internal) total exposure at low doses, to which the RCTs population was subjected. In some cases, however, the internal radiation doses to the thyroid gland (TG) were high.

Of considerable interest was also the health status of descendants of individuals exposed as a result of the Chernobyl accident.

MAIN BODY

Medical management and long-term health effects of radiation exposure among nuclear accident emergency responders

Approximately 600 emergency workers (plant personnel and firefighters) received the highest doses. They were exposed to acute high-dose radiation, including lethal doses, in the first days after the accident. The predominant exposure was due to whole-body external gamma radiation at a high dose rate of beta radiation to the skin surface. In contrast, neutron exposure and inhalation intake of radionuclides were negligible.

In the first hours after the accident, medical assistance to the affected individuals was provided by the on-duty staff of the Chernobyl NPP health post and emergency medical services. Twelve hours after the accident, the emergency radiological team from the clinic of the Institute of Biophysics of the USSR Ministry of Health* (hereinafter referred to as the IBPh) commenced operations. The team assessed the radiation situation and conducted medical triage of the irradiated emergency workers to determine the need for and timing of specialized medical care.

After triage of casualties suspected of acute radiation syndrome (ARS), they were transported to the IBPh clinic by special aircraft flights. Within 48 h, 129 irradiated individuals were hospitalized, of whom 84 were diagnosed with moderate, severe, and extremely severe ARS. At the clinic, radiation dose verification was performed using cytogenetic methods [1]. The activity of incorporated radionuclides was measured using human radiation counters[2] [2]. Radiation doses received by ARS patients from whole-body external gamma radiation and in the bone marrow ranged 0.8–16 Gy. Skin doses from beta radiation, estimated in eight ARS patients, were 10–30 times higher than whole-body doses from external radiation and reached 400–500 Gy[3] [3].

Of the 134 patients with verified ARS, 28 individuals died within the first four months. The primary cause of death was acute bone marrow syndrome, induced by exposure to high doses of gamma radiation. The immediate causes of death included infectious complications, intoxication, and progressive multiple organ failure [3]. Additionally, two emergency workers died shortly after the accident from injuries sustained during the incident [4].

Allogeneic bone marrow transplantation was performed in thirteen patients. Six additional patients received transplants of human fetal liver cells. All of these patients died, except for one individual, in whom, as later discovered, the activity of the native bone marrow recovered, leading to transplant rejection. In three cases, the fatal outcome may have been associated with unsuccessful bone marrow transplantation. Based on the treatment results for patients with ARS, it was concluded that bone marrow transplantation is indicated only for patients with irreversible suppression of hematopoiesis caused by acute total relatively uniform gamma radiation exposure at doses of 8–10 Gy [4, 5].

All patients with severe and extremely severe bone marrow syndrome had radiation-induced skin lesions. These lesions exacerbated suppression of hematopoiesis, especially in cases of damage to 50% of the body surface, and were complicated by infections. It is assumed that skin injuries played a major role in at

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* Currently, the clinic of the State Scientific Center of the Russian Federation — Burnasyan Federal Medical Biophysical Center of Federal Biological Agency.

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least nineteen fatal outcomes and significantly aggravated the course of ARS [2, 6]. Patients whose skin did not heal within 50–60 days underwent skin grafting. Gastrointestinal syndrome was observed in fifteen patients, and radiation pneumonitis in eight.

Subsequent long-term follow-up of individuals who survived ARS showed nearly complete restoration of hematopoiesis within several months after radiation exposure, whereas recovery of the immune system took at least six months. Full normalization of T-cell immunity required several years.

The main long-term medical consequences of ARS were radiation-induced skin lesions and cataracts. Skin injuries depended on the radiation dose and the severity of ARS, ranging from mild degenerative changes to the development of severe scars and ulcers. For example, between 1990 and 1996, 15 individuals with extensive skin lesions underwent surgical treatment. Radiation cataracts developed in many patients with moderate and severe ARS during the first few years after the accident.

Most men who survived ARS experienced sexual dysfunction until 1996; however, 14 healthy children were born to some of them within the first five years after the accident.

In the first decade after the accident, individuals who had survived ARS showed a high prevalence of nervous system disorders, cardiovascular diseases, and gastrointestinal diseases. However, the incidence of these conditions did not correlate with the ARS severity, suggesting that these diseases were more likely of non-radiation origin.

Among the causes of death in the long-term follow-up period, non-neoplastic systemic diseases predominated — specifically, disorders of the cardiovascular system, respiratory system, and digestive system. Neoplasms (cancer) were less common [7]. Given the stochastic nature of the pathology leading to fatal outcomes in individuals who survived ARS, the relationship between long-term causes of death and radiation exposure is not evident. The fatal cases appear to have been caused by non-radiation factors.

Medical and biological consequences of radiation exposure in accident cleanup workers

As noted earlier, more than 500 thousand various specialists participated in the emergency response to the accident and subsequent recovery operations. June 1986 marked the beginning of the formation of the All-Union Distributed Registry of Individuals Exposed to Radiation. This registry included Chernobyl accident cleanup workers and later became the foundation of the National Radiation and Epidemiological Registry [8, 9].

Radiation monitoring and radiation doses received by cleanup workers. The release of radioactive materials from the damaged reactor began on April 26, 1986, and, according to some estimates, continued for 10–15 days. Short-lived radionuclides — such radioisotopes as ^{131}I, ^{103,106}Ru, ^{144}Ce, ^{140}Ba, etc. — were the main contributors to radiation doses at the early stage of the accident. Later, cesium radioisotopes (^{137}Cs, ^{134}Cs) played an increasingly significant role in dose formation, while strontium isotopes (^{90}Sr) contributed much less. Radioisotopes of transuranic elements (^{238,239,240,241}Pu, ^{241}Am), although present in the radioactive releases, made a negligible contribution to the total radiation dose [10]. The primary exposure pathway for cleanup workers was external gamma radiation from radioactive materials deposited on the ground and building surfaces.

Radiation surveillance and exposure doses among Chernobyl accident cleanup workers. The release of radioactive materials from the damaged reactor began on April 26, 1986, and, according to some estimates, continued for 10–15 days. Short-lived radionuclides — such radioisotopes as ^{131}I, ^{103,106}Ru, ^{144}Ce, ^{140}Ba, and others — were the main contributors to radiation doses at the early stage of the accident. Later, cesium radioisotopes (^{137}Cs, ^{134}Cs) played an increasingly significant role in dose formation, while strontium isotopes (^{90}Sr) contributed much less. Radioisotopes of transuranic elements (^{238,239,240,241}Pu, ^{241}Am), although present in the radioactive releases, made a negligible contribution to the total radiation dose [10]. The primary exposure pathway for cleanup workers was external gamma radiation from radioactive materials deposited on the ground and building surfaces.

Dosimetric monitoring of cleanup workers was organized on a large scale approximately one month after the accident [11]. Even among cleanup workers seconded from enterprises of the USSR Ministry of Medium Machine Building, less than half of the personnel were provided with individual dosimeters [12]. By decision of the USSR Government Commission dated May 28, 1986, individual dosimetric control (IDC) was assigned to three agencies: the USSR Ministry of Defense, the USSR Ministry of Medium Machine Building, and the USSR Ministry of Energy. The USSR Ministry of Internal Affairs and the USSR Committee for State Security also carried out dosimetric monitoring independently until September 1987. Since 1986, personnel from more than 600 organizations across 49 ministries and agencies of the USSR were subject to IDC. The largest number of cleanup workers were assigned to units of the USSR Ministry of Energy [12].

The dosimetric data collected in the National Radiation and Epidemiological Registry (NRER) can be divided into three types:

- values from an individual dosimeter worn by a specific cleanup worker;
- group dose values based on readings from an individual dosimeter worn by one member of the group;

- estimates of route specific doses, derived from the average exposure rate in the work area and the duration of the group's presence there.

Currently, 142.9 thousand participants in the accident cleanup have information on external radiation doses received in the accident zone, which accounts for 71.4% of the total number of cleanup workers registered in the NRER. For comparison: in the Japanese registry of survivors of the atomic bombings of Hiroshima and Nagasaki, out of 120,300 registered individuals, 86,600 people (72.0%) have data on reconstructed individual doses. An analysis of the quality of dosimetric data for cleanup workers entered into the NRER showed no obvious contradictions between the parameters of the radiation environment in radioactive contamination zones, the nature of the work performed, and the doses recorded in the registry. Furthermore, a statistical analysis of dosimetric data for cleanup workers registered in the NRER revealed a small proportion of individuals whose doses lack an acceptable degree of reliability [12].

The period of radiation exposure for cleanup workers was limited to several months [9]. The accumulated average external radiation dose for all cleanup workers, regardless of the year they entered the accident zone, was 106 mGy. Cleanup workers who entered the accident zone in 1986 received, on average, one-and-a-half times higher radiation doses (more than 150 mGy). The distribution of the average dose rate among cleanup workers who received doses exceeding 150 mGy followed a log-normal distribution, with a mean value of approximately 3 mGy/day. Due to the established regulatory limit for radiation exposure during the response to radiation accidents, the total radiation doses for 97.5% of cleanup workers did not exceed 250 mGy.

Health monitoring and vital status. The NRER is a state information system containing personal data of individuals exposed to radiation as a result of the Chernobyl nuclear power plant accident, other radiation accidents and incidents, and nuclear tests. It was created to ensure lifelong monitoring of health changes in such individuals. In accordance with Russian legislation, the NRER registers citizens of the Russian Federation who belong to one of 24 accounting categories. Twelve of these categories pertain to individuals exposed to radiation due to the Chernobyl accident, as well as their descendants. The NRER system operator is the Ministry of Health of the Russian Federation. The lead organization within the NRER system is the A. Tsyb Medical Radiological Research Centre — branch of the National Medical Research Radiological Centre.

The NRER is a geographically distributed information system that includes: a unified federal database, regional segments (in the constituent entities of the Russian Federation), and four departmental sub-registries (under the Ministry of Defense of Russia, the Ministry of Internal Affairs of Russia, the Ministry of Emergency Situations of Russia, and the Federal Medical-Biological Agency of Russia). The regional segments of the registry are maintained by the authorized executive bodies of all constituent entities of the Russian Federation [11].

Currently, 834,200 individuals are registered in the NRER, of which more than 763 thousand belong to the "Chernobyl cohort", including:

- more than 200,000 cleanup workers involved in the aftermath of the accident; more than 370,000 residents of the Bryansk, Kaluga, Oryol, and Tula regions who live in the resettlement zone and the zone with the right to resettlement;
- more than 50 thousand descendants of the cleanup workers.

Collection of individual medical and dosimetric information is carried out at the regional and municipal levels during mandatory special medical surveillance (specialized preventive health check-up) and in the process of seeking medical care. The average annual coverage rate of cleanup workers by medical examinations, both over the entire observation period as a whole and over the past 10 years, is approximately 80%. In the first 15 years after leaving the radiation-affected zone, the rates of primary and overall morbidity among cleanup workers for many disease classes significantly exceeded the corresponding rates for reference population groups in the Russian Federation matched by age and sex characteristics. In subsequent years, this excess steadily declined. Primarily, the excess morbidity is explained by the implementation of specialized диспансеризация among cleanup workers. The only disease class demonstrating a steady increase in primary morbidity throughout the entire observation period is the Neoplasms class.

The overall mortality rate among cleanup workers over the entire observation period is statistically significantly lower (by an average of 15%) than the mortality rate in the reference population group of the Russian Federation matched by age and sex characteristics. Their longer life expectancy is explained, on the one hand, by the so-called "healthy worker effect", and on the other hand, by a higher level of socio-medical care provided to cleanup workers. The mortality rate from malignant neoplasms (MN) over the entire observation period was statistically significantly higher than the control rate in the reference group of the male population of the country — by 6%. According to NRER data as of early 2026, approximately 52.5% of the total number of cleanup workers registered in the registry have died, of whom:

- 42.7% died from cardiovascular system diseases;
- 18.5% died from malignant neoplasms;
- 15.8% died from injuries and poisonings.

Radiobiological effects. Preclinical effect studies received particular attention, as they were considered biological markers of individual radiation dose and predisposition to radiation-induced pathology. Cytogenetic and molecular genetic changes in peripheral blood lymphocytes (PBL) of cleanup workers proved to be sufficiently reliable biomarkers of radiation exposure. In the early period after the accident, a high level of unstable-type chromosomal aberrations (dicentrics and centric rings) was observed [13, 14], which decreased over time but remained statistically significantly elevated compared to non-exposed individuals for more than twenty years [15]. In the long-term follow-up period, the level of stable translocations was recorded, detected by fluorescence *in situ* hybridization (FISH) [16]. However, good comparability of cytogenetic data with physical dosimetry was noted only for a subset of the examined cleanup workers. At the same time, a high individual variability in the frequency of stable chromosomal aberrations induced by low radiation doses was observed [17]. In subsequent years, the level of translocations in PBL decreased to a certain plateau, but its value clearly correlated with the initial radiation dose estimate, which confirms the significance of stable markers for retrospective dosimetry [18].

The results of somatic mutagenesis assessment based on the analysis of mutations in the T-cell receptor gene of blood lymphocytes (TCR mutations) indicate an increase not only in the early period after radiation exposure, but also after a long time has elapsed. For example, in a subset of cleanup workers exposed to radiation doses up to 2 Gy, an increased frequency of TC-mutant lymphocytes was detected in the long-term period after the accident. Moreover, this indicator remained virtually unchanged over time following radiation exposure [19, 20].

For many years, dose-dependent changes in adaptive immunity, predominantly T-cell-mediated, persisted among cleanup workers. In the early period after radiation exposure, an increase in the number of T-lymphocytes and T-helper cells was observed compared to non-exposed individuals. The most active increase in the T-helper cell population was recorded in cleanup workers exposed to low radiation doses [21]. However, 3 months after radiation exposure, a decrease in the levels of T-lymphocytes and T-helper cells was observed, which also correlated with the radiation dose. In later follow-up periods, the reduced frequency of $CD3^+$ cells and $CD3^+CD4^+$ cells exhibited a persistent pattern [22, 23], manifesting as:

- an imbalance in the $CD4^+/CD8^+$ ratio[4];
- an increased level of regulatory T-cells in the blood [24];
- elevated levels of pro-inflammatory cytokines IL-1β, IL-6, IFN-γ, and TNF-α in blood serum [23].

Medical consequences. No ARS cases were registered among cleanup workers. The main concern was long-term effects, which were not specific to radiation exposure (multifactorial pathology) and had a stochastic nature. The probability of their development is determined by the radiation dose. The most reliable data on the consequences of radiation exposure among cleanup workers were obtained from a cohort of 66,000 male cleanup workers who entered the accident zone in 1986-1987. This cohort is supported by dosimetric data and health status information for the entire observation period. The average age of the cleanup workers at the start of the observation period was 34 years [25].

In the structure of leukemia incidence over the period 1986–2007 (198 cases registered) [26], chronic forms predominated, with equal proportions of myeloid and lymphoid types. A statistically significant excess risk of leukemia incidence, excluding chronic lymphocytic leukemia (CLL), was observed only during the first ten years after the accident — both when compared to national rates and when using internal control. The radiation risk for CLL was statistically insignificant. The excess of the incidence rate in the cohort over the corresponding rate for the Russian male population during the period 1986–1997 amounted to 89% (age-standardized ratio 1.89 (95% CI [1.42; 2.45]) [27]. Subsequently, in 1998–2018, this indicator was 23% lower than the Russian rate (age-standardized ratio 0.77 (95% CI [0.64; 0.93])) [27].

When using the linear no-threshold (LNT) model of radiation risk, the excess relative risk coefficient per 1 Gy (ERR/Gy) for the first ten years after the accident was 4.41 (90% CI [0.24; 14.23]), and subsequently became statistically insignificant [27]. According to the LNT model, approximately 32% of leukemias (excluding CLL) in the first ten years after radiation exposure can be attributed to radiation effects.

Since follow-up monitoring of cleanup workers in 1998–2025 confirmed the absence of radiation-related leukemia risk, it can be assumed that radiation-induced leukemias in cleanup workers had already fully manifested by 1998. The excess number of such cases amounted to 8, which is the average value between the lifetime predictions of the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The lifetime projection of radiation-induced leukemia cases among cleanup workers after 2020 is estimated at 1 case according to the ICRP model and 18 cases according to the UNSCEAR model.

Analysis of the dose-response relationship showed agreement between estimates of relative radiation risk (RR) from the LNT model and non-parametric RR estimates relative to the control group of cleanup workers with radiation doses below 0.05 Gy, taking into account their 90% confidence intervals [27]. Statistically significant RR estimates were observed only at doses exceeding 0.15 Gy. Thus, for radiation doses below 0.15 Gy, the LNT model of radiation leukemia risk in cleanup workers was conservative and led to overestimated radiation risk assessments [27].

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The incidence of solid malignant neoplasms (MNs) during the observation period 1992–2019 was 11% higher than the rate for the Russian male population (95% CI [9; 13]). At the same time, mortality from MNs did not differ from the national average for Russia. Within the framework of the LNT model, the excess relative risk per 1 Gy (ERR/Gy) for the incidence of solid MNs was 0.62 (95% CI [0.29; 0.98]), and for mortality, ERR/Gy was 0.74 (95% CI [0.32; 1.22]). Radiation risks of incidence and mortality from solid MNs were mainly determined by neoplasms of the esophagus, stomach, and colon (ERR/Gy): 0.89 (95% CI [0.20; 1.74]) for incidence, and ERR/Gy at the level of 0.77 (95% CI [–0.05; 1.81]) for mortality. ERR/Gy for the incidence of MNs of the trachea, bronchi, and lung was 0.85 (95% CI [0.21; 1.62]), and for mortality, 0.85 (95% CI [0.13; 1.72]). This can be partially attributed to the highest prevalence of tumors in these locations, which account for more than half of all cases of solid MNs.

A quantitative comparison of projected estimates of lifetime radiation risk of MNs, calculated using radiation risk models from the ICRP, the UNSCEAR, and the NRER, in the cohort of cleanup workers showed that when using own estimates after 2020, 1297 excess cases of MNs are expected in the cohort of Russian cleanup workers. This is 2.4 times higher than the values obtained from calculations using international models.

As the follow-up period increases, the trend of a slight increase in radiation risks for solid malignant neoplasms (MNs) persists after 2019. The latest ERR/Gy estimates, made as of early 2026, are 0.73 (95% CI [0.43; 1.07]) and 0.76 (95% CI [0.37; 1.20]) for incidence and mortality, respectively. Non-parametric RR estimates in dose intervals, similarly to those for leukemias, were statistically significant only for radiation doses of 0.15 Gy and higher [27]. This indicates the conservativeness of radiation risk estimates for solid MNs in cleanup workers in the low-dose radiation exposure range when using the LNT model.

Follow-up monitoring of the cleanup worker cohort showed an increase in the incidence of blood disorders (ICD-10: D50–D89). In this case, the LNT model adequately describes the risk magnitude at various levels of radiation exposure, with ERR/Gy equal to 0.59 (95% CI [0.23; 0.99]) [8]. Of note are the high radiation risks for the development of aplastic anemias (ICD-10: D60–D61), where ERR/Gy was 5.56 (95% CI [0.53; 20.67]). For blood and hematopoietic organ disorders not classified as anemias or hemorrhages (ICD-10: D70–D77), ERR/Gy was 2.25 (95% CI [0.97; 3.95]), and for immunodeficiency states (ICD-10: D80–D89), ERR/Gy was 2.01 (95% CI [0.53; 4.10]). In contrast to leukemias, for which the radiation risk manifested within the first ten years after exposure [6], the excess risk of aplastic anemias has persisted for over 30 years.

The ERR/Gy incidence coefficient for cardiovascular system diseases (ICD-10: I00–I99) is statistically significant and amounts to 0.57 (95% CI [0.46; 0.68]), as is the mortality coefficient — 0.42 (95% CI [0.19; 0.60]). It should be noted that in the Japanese cohort of atomic bomb survivors, the radiation risk of mortality from cardiovascular system diseases for the male population was estimated at a 6-fold lower ERR/Gy coefficient, amounting to 0.07 (95% CI [–0.001; 0.16]) [28].

Non-parametric RR estimates based on mortality data confirm the validity of the LNT model, which contradicts the ICRP's claims of a threshold relationship between the incidence of cardiovascular system diseases and radiation dose level, with a threshold value of 0.5 Gy.

The results of recent studies on cataract incidence (ICD-10: H25–H26) indicate a significant dependence of the prevalence rate of this nosology on the dose of external gamma radiation [11]. The obtained estimates of dose thresholds do not support the need to reduce the maximum permissible dose to the eye recommended by the International Commission on Radiological Protection (ICRP) [29].

The results of non-parametric RR model assessments indicate that the radiation effect, manifested as an increase in the incidence of endocrine system diseases, nutritional disorders, and metabolic abnormalities (ICD-10: E00–E90), as well as nervous system diseases (ICD-10: G00–G99), may be threshold-based [30]. The greatest contribution to excess morbidity from endocrine system diseases comes from iodine deficiency (E01), goiter (E04), thyroiditis (E06), and type 2 diabetes mellitus (E11). For nervous system diseases, the main contributors are polyneuropathies and other disorders of the peripheral nervous system (G60–G64), as well as other nervous system disorders (G90–G99).

A detailed analysis of the risk of respiratory system diseases and digestive system diseases allowed estimating the parameters of the LNT model of radiation risks [31, 32]. Non-parametric RR estimates confirmed the validity of the LNT models. The average ERR/Gy coefficient for morbidity from respiratory system diseases across the entire cohort of cleanup workers was 0.21 (95% CI [0.11; 0.32]), and for digestive system diseases — 0.33 (95% CI [0.22; 0.44]). Increased morbidity from respiratory system diseases is driven by conditions such as influenza and pneumonias (J09–J18), other upper respiratory tract diseases (J30–J39), as well as chronic lower respiratory tract diseases, including chronic obstructive pulmonary disease (COPD, J44) and asthma (J45–J46). The radiation risk of morbidity from digestive system diseases is primarily attributable to gastric and duodenal ulcers, gastritis and duodenitis, chronic hepatitis not classified elsewhere, as well as gallbladder and biliary tract diseases.

Statistically significant radiation risks have also been obtained for mental disorders (F00–F99), musculoskeletal system diseases (M00–M99), and genitourinary system diseases (N00–N99), confirming the need for a more detailed analysis of the incidence of these nosologies as a function of radiation dose [33]. It should be noted that for infectious and parasitic diseases (A00–B99), ear diseases (H60–H95), benign neoplasms (D10–D36), as well as skin and subcutaneous tissue diseases (L00–L99), no radiation risk was detected in cleanup workers despite their high prevalence [16].

An assessment of the dynamics of radiation risks for morbidity among cleanup workers from major non-cancer diseases shows that the values of these risks over the entire follow-up period are determined by disease cases that arose in the first 10–15 years after the accident. It is important to note that the radiobiological mechanisms underlying the increase in morbidity and mortality from the aforementioned non-cancer diseases are insufficiently studied. The most likely pathogenetic mechanism of multi-organ pathology in cleanup workers is chronic non-specific inflammation induced by radiation exposure, which is mediated by a pro-inflammatory immune status [34].

Medical consequences for the RCT population of the Russian Federation

Emergency releases of radioactive compounds have caused contamination of territories in the Russian Federation, particularly in the Bryansk, Kaluga, Oryol, and Tula regions.

Radiation-hygienic monitoring and population radiation doses. Operational dosimetric monitoring of the radiation situation and its dynamics was organized in the very first days after the accident. The purpose of radiation-hygienic monitoring — both at the early stage of a radiation accident and at its current stage — is to obtain a set of initial data required for calculating radiation doses received by residents of settlements located in RCTs. In the early period, radiation doses were primarily used to develop protective measures and assess their effectiveness. In subsequent periods, monitoring makes it possible to analyse the dynamics of the radiation situation and evaluate the medical-biological consequences of the accident. Depending on changes in the situation (due to the physical decay and migration of radio-nuclides that are significant at a given time) and the monitoring objective, the set of monitored parameters is subject to change.

External exposure of the population is caused by the decay of gamma-emitting radio-nuclides present in the environment. Immediately after the accident, the elevated gamma background was determined by short-lived radio-nuclides (^{131}I, ^{103,106}Ru, ^{144}Ce, ^{140}Ba, etc.), and later — by cesium radioisotopes (^{134}Cs и ^{137}Cs). In the first weeks after the accident, iodine isotopes were the main dose-forming radio-nuclides for internal exposure of the population. The primary route of their intake into the bodies of RCTs residents was through consumption of cow's milk and fresh greens. From the third decade of May 1986, ^{134}Cs и ^{137}Cs became the main dose-forming nuclides, entering the body mainly via milk and meat, as well as through plant-based and natural food products of local origin. The contribution of strontium isotopes (^{89,90}Sr) to the internal radiation dose of the Russian population is insignificant (1–5%).

In settlements classified as radioactive contamination zones, systematic monitoring of the radiation situation is organised. The settlement survey programme is developed taking into account:

- their classification as radioactive contamination zones;
- the priority of settlements with high levels of ^{137}Cs soil contamination.

The most extensive monitoring is carried out in the heavily contaminated Bryansk region. Residents of some settlements undergo individual dosimetric monitoring using TLD dosimeters. As part of radiation-hygienic food monitoring, radio-nuclide content (^{137}Cs and ^{90}Sr) is analysed in milk and potatoes produced in residents' private households, mushrooms. In settlements, systematic measurements of the exposure rate of gamma radiation are conducted[5] [35].

To determine population protection measures, methodologies have been developed for assessing radiation doses both under conditions of no active radiation protection measures and for actual radiation doses — on average for residents of a settlement, for a critical group of residents, and for accumulated radiation dose[6]. To classify a settlement into a specific zone, the average annual effective dose ($AAED_{90}$) among residents is estimated for living and conducting economic activities without active radiation protection measures. When assessing the average accumulated effective dose (AAcED), results from actual radiation dose assessments for the population are used. The most reliable information on actual population exposure levels is obtained from radiation monitoring data collected in contaminated territories. Based on these results, the average annual effective dose for residents of a settlement (AAED-S) is estimated. The average annual effective dose for the critical group of settlement residents is defined as the mean dose received by the top 10% of residents who have the highest individual radiation doses compared to the rest of the population.

By 2020, the average effective dose for the critical population group in 386 settlements of the Bryansk, Tula, Oryol, and Kaluga regions amounted to approximately 40 mSv [36]. The highest thyroid doses were received by the population evacuated from the 30 km zone. The average dose was about 500 mGy, while thyroid radiation doses in children under three years of age

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[5] On the state of sanitary and epidemiological well-being of the population in the Bryansk Region in 2024. State Report. Bryansk: Department of Rospotrebnadzor for the Bryansk region; 2024 (In Russ.).

[6] Assessment of radiation doses to the population of the Russian Federation due to the Chernobyl accident: Collection of methodological documents. 3rd edition. St. Petersburg; 2011.

reached 50 Gy [37]. Average thyroid radiation doses from ^{131}I among residents of settlements located in areas with a ^{137}Cs contamination density exceeding 37 kBq/m^2, in children under one year of age, were as follows:

- Bryansk region — up to 1.3 Gy;
- Kaluga region — 0.16 Gy;
- Oryol region — 0.23 Gy;
- Tula region — 0.19 Gy.

Maximum individual doses in children under three years of age in the Bryansk region reached 10 Gy [38].

Medical and biological consequences of radiation exposure in the population. Analysis of medical consequences prior to the establishment of the irradiated population registry was carried out using the geographical method. A distinctive feature of this method is the assessment of radiation effects on the population of a specific territory (for example, a district or region) using nationwide (or other) statistical data on population size, its dynamics, and age-and-sex structure. Such studies use average group doses estimated for individual territories (districts) and age groups.

After the NRER establishment in the Russian Federation, it became possible to conduct analytical studies (cohort studies, case-control studies) that provide reliable information on the medical consequences of radiation exposure. These studies are based on long-term health monitoring of the population throughout their lives after the accident, using individual radiation doses of cohort members. According to current standards, all individuals registered in the NRER undergo annual medical examinations, which ensures high completeness and quality of the data.

The results of cytogenetic studies conducted among evacuees and RCTs residents — carried out to assess radiation doses in the first years after the accident — indicated an increased level of aberrant lymphocytes in blood and unstable-type chromosomal aberrations compared to non-irradiated individuals [39]. Later, an increase in the frequency of stable-type chromosomal aberrations (predominantly translocations and inversions) in peripheral blood lymphocytes (PBLs), detected by the FISH method, was established [40]. Stable-type chromosomal aberrations persisted for over 20 years and indicated the possibility of cytogenetic dose assessment nearly 30 years after the accident using the FISH method [16, 18, 41].

Regarding medical effects, no ARS cases or tissue radiation reactions were observed in the population, as well as in cleanup workers. Concerns were raised about multifactorial diseases, the likelihood of developing which could increase in the long term after radiation exposure. However, long-term analysis of the incidence of leukaemias, solid malignant neoplasms (MNs) of various localisations, non-cancer diseases (diseases of the circulatory system, respiratory system, thyroid gland, etc.) in the irradiated population did not reveal any influence of radiation exposure on their incidence rates — with the exception of thyroid cancer (TC).

According to the NRER, the radiation risk of leukaemia for the RCTs population is not statistically significant, although the average value of excess radiation risk still exceeded the zero level and amounted to 7%.

The radiation risk of developing solid MNs, including breast cancer risk in women, for the population of radioactively contaminated territories is also not statistically significant. This is explained by the low doses of total population exposure. If conservative risk projections based on ICRP risk models are followed, the excess radiation risk of morbidity from solid MNs among the population should be expected at a level 1% above spontaneous morbidity rates. With such a small expected risk, a longer period of health monitoring of the population living in contaminated territories will be required to detect it.

A distinctive feature of population exposure following the Chernobyl accident was the high-dose ^{131}I impact on the TG in individuals who were children or adolescents at the time of the accident. The increased TC incidence in this group remains the only proven effect of radiation exposure among populations living in contaminated territories [11, 42, 43]. For example, in a large-scale case-control study conducted among individuals residing in the most contaminated areas of Belarus and the Russian Federation, the odds ratio for TC development at a dose of 1 Gy was 5.2 (95% CI [2.2; 8.2]) [42]. The results are generally consistent with estimates from studies in cohorts of residents of:

- Ukraine: relative risk, RR/Gy — 2.9 (95% CI [1.4; 7.3]);
- Belarus: RR/Gy — 3.2 (95% CI [1.8; 6.5]);
- Russian Federation: RR/Gy — 5.6 (95% CI [3.7; 8.0]) [43–45].

The excess risk was detected 4–5 years after exposure and, despite its decline over time, remains statistically significant for decades after the accident. This is due not only to the carcinogenic effect of ^{131}I, but also to TC screening effect. Analysis of the Russian cohort showed that in the period 1991–1995, the screening coefficient for children and adolescents was at its maximum and amounted to 11.9. After 1996, however, the coefficient decreased by half [43].

It should be noted that the value of the excess relative risk per gray (ERR/Gy) for TC in individuals exposed to radiation during childhood and adolescence shows high variability across different studies. This necessitates continued research into the dependence of TC risk — primarily on iodine deficiency, the influence of non-radiation factors, and uncertainties in thyroid radiation dose estimates. At the same time, convincing evidence has been obtained that individuals who took stable iodine supplements in schools and summer camps after the Chernobyl accident had a significantly lower TC risk compared to those who did not take iodine supplements. Research findings demonstrate the critical importance of prophylactic intake of stable iodine during nuclear power plant accidents — especially in regions with iodine deficiency [42].

Estimates of the proportion of radiation-induced TC cases also show high variability. The UNSCEAR estimates the proportion of excess radiation-associated cancer cases at 60% for children and 25% for adolescents, respectively[7]. In the Russian cohort of children residing in the most contaminated areas, it was shown that out of 423 cancer cases identified in 1991–2019, 21% (i.e., 87 cases) can be attributed to radiation exposure. At the same time, among the group of children under 4 years of age, 58% (i.e., 60 cases) are radiation-induced. The difference in the proportion of radiation-induced cases is mainly determined by significantly higher thyroid radiation doses in children under 4 years compared to older age groups [43].

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Molecular mechanisms of TC in irradiated individuals. Molecular genetic studies are aimed at investigating radiation-specific genetic changes in thyroid cancer (TC) cells in individuals exposed to radiation during childhood. This allows establishing the radiation etiology of cancer in each specific case. Particular attention has been paid to gene rearrangements; deletions; point mutations; gene copy number increases; aberrant methylation in genes responsible for cell proliferation, differentiation and apoptosis. The following candidate genes were analysed: *BRAF*, *HRAS*, *KRAS*, *NRAS*, *PTEN*, *PIK3CA*, *AKT1*, *CTNNB1*, *TP53*, *IDH1*, *EGFR*, *HCTC*, *RET*, *NTRK1* and *TERT* (TERTp). The dysfunctional activity of these genes plays a significant role in the oncogenesis of follicular and papillary TC. As potential oncological markers, genes encoding receptors of microenvironment cells were also considered, in particular: *CXCL10*, *AGTR1*, *CTGF*, *FAM3B*, *IL11*, *IL17C*, *PTH2R* and *SPAG11A* [46].

It has been established that tumour growth and progression of TC are closely linked to somatic point mutations in the *BRAF*, *RAS* and *RET* genes. Activation of these genes through mutations or rearrangements is the main initiator of TC development via a signalling pathway involving mitogen-activated protein kinase (MAPK) and phosphoinositide-3-kinase (PI3K). This enhances nuclear translocation of the *ERK* gene and modifies the transcription of target genes [47, 48].

It is assumed that molecular rearrangements caused by radiation exposure and initiating malignant transformation of thyroid follicular cells may be unique and specific to radiation exposure. In particular, in the first ten years after the Chernobyl accident, variants of papillary thyroid cancer (PTC) with *RET/PTC3* rearrangements were quite common. In later periods, however, *RET/PTC1* rearrangements became predominant [49, 50].

The *RET* gene encodes a membrane protein of the tyrosine kinase receptor family. Under normal conditions, it is either not expressed or expressed at a very low level in thyroid follicular cells and is classified as a proto-oncogene. *RET* activation can occur through chromosomal inversion or translocation, which lead to fusion of the coding region of the *RET* intracellular domain with the 5’-end of heterologous genes. The resulting chimeric *RET/PTC* sequence encodes oncoproteins that trigger the development of papillary thyroid carcinoma. To date, more than 13 *RET/PTC* variants have been registered. These variants differ in terms of the 5’-partner gene involved in the rearrangement. However, the most common types in thyroid cancer cells are: *RET/PTC1* (fusion with the *CCDC6* gene), *RET/PTC3* (fusion with the *NCOA4* gene) [51]. Despite early research findings indicating that *RET/PTC* rearrangements are specific to radiation-induced TC, current evidence suggests that they are also quite common in sporadic TC [49, 52, 53].

It is likely that the more frequent detection of *RET/PTC3* and *RET/PTC1* rearrangements in TC cells is due to the high sensitivity of these regions to genetic damage — not only as a result of ionising radiation exposure, but also due to other genotoxic factors. *RET/PTC* rearrangements are now recognised as the predominant driver mutations not only in radiation-induced cancer, but also in sporadic PTC in children [54].

The V600E point mutation in the *B-RAF* oncogene (a substitution of thymine with adenine at nucleotide 1799) is one of the most frequent mutations in cells of sporadic PTC in adults, and is rarely found in follicular cancer cells [55]. This mutation promotes tumour initiation and metastasis [56]. However, in PTC cells from individuals exposed to radiation after the Chernobyl accident, the *B-RAF* V600E mutation was significantly less common than *RET/PTC* rearrangements [57].

Thus, the question of the existence of specific radiation-induced molecular markers of TC remains open.

Health status of descendants

According to the UNSCEAR and the ICRP, there is currently no convincing evidence in humans that parental exposure to ionising radiation leads to any health changes in their descendants. However, in children

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[7] Evaluation of data on thyroid cancer in regions affected by the Chernobyl accident. New York: United Nations; 2018.

exposed *in utero* as a result of the atomic bombings of Hiroshima and Nagasaki, a reduction in cognitive abilities has been observed. This reduction is dependent on both the radiation dose received and the gestational age at the time of exposure. These findings have generated significant interest in similar studies following the Chernobyl accident.

Transgenerational effects. Special attention is focused on the possibility of identifying transgenerational effects in first-generation descendants who were not themselves exposed to radiation, but were born to accident liquidators after their radiation exposure or to RCTs residents. Such effects, which have been documented only in animal experiments, are attributed to pre-conceptional (before conception) irradiation of parental gonads. When assessing the health status of descendants, a wide range of health parameters were evaluated:

- anthropometric indicators of newborns;
- incidence of various pathologies, including MNs and leukaemias;
- immune status;
- frequency and pattern of congenital malformations;
- perinatal, infant and child mortality;
- and other parameters.

As a result of radiological epidemiological studies in a cohort of children of liquidators registered in the NRER; includes 11 698 liquidator fathers and 15,450 of their children born after leaving the accident zone, no statistically significant association was found between the MNs incidence and congenital malformations in liquidators' children and the level of external radiation dose received by their fathers [58]. In children born in resettlement zone territories and in zones with the right to resettlement, no statistically significant dependence of the incidence of congenital malformations on the radiation dose received by their parents has been identified to date. A conservative estimate, performed in accordance with the 2007 ICRP recommendations, showed that the possible proportion of radiation-induced hereditary diseases in descendants born to parents who lived in RCTc before 2000 may reach 0.4% of the national average indicators for Russia[8].

When evaluating the results of clinical and epidemiological observations of descendants, it is necessary to note their inconsistency [58–60]. It is noteworthy that in cases where effects were detected in descendants, no evidence was provided to link them to the genetic radiation dose received by the parents. The authors also fail to take into account that the descendants themselves lived in RCTs and were exposed to both in utero and postnatal radiation. Other important challenges in transgenerational effect studies include insufficient statistical power of the studies and low levels of parental gonadal radiation doses [61].

In several studies, authors explain the observed health changes in descendants by radiation-induced genomic instability (RIGI), which may develop as a result of genetic and epigenetic changes in parental germ cells following radiation exposure [62–64].

To provide evidence of RIGI in descendants and their parents, the frequency of chromosomal aberrations was analysed — their levels increase significantly in the presence of RIGI. In some cytogenetic studies, an elevated level of unstable and stable chromosomal aberrations in PBLs has been observed in descendants of irradiated individuals [16, 62, 65]. However, it should be noted that the dependence of cytogenetic parameters on the pre-conceptional radiation dose to parental gonads has not been investigated. Furthermore, interpretation of the results of cytogenetic studies in descendants living in contaminated areas is complicated by the inability to exclude the influence of their own in utero and postnatal radiation exposure.

Analysis of gene mutation frequency — which also increases significantly in the presence of RIGI — did not reveal an elevated mutation rate in the T-cell receptor gene among descendants of irradiated parents. In contrast, their parent-liquidators showed an increased mutation rate not only in the early period after radiation exposure, but also many years later [19, 20, 66]. Analysis of de novo mutations in children born after the accident to liquidators and residents of RCTs also failed to find evidence of a significant impact from pre-conceptional irradiation of parental gonads: up to 4,080 mGy in fathers and up to 550 mGy in mothers [67]. Thus, cytogenetic and molecular genetic studies do not allow us to conclude that transgenerational effects and RIGI are present in descendants of liquidators and children born after the accident who lived in RCTs.

Effects of in-utero radiation exposure. The extraordinary significance of research into the effects of in-utero radiation exposure is determined primarily by the high radiosensitivity of the embryo and fetus. An important component of radiation exposure after the accident was ^{131}I, which entered the bodies of pregnant women through the alimentary route and affected the intrauterine development of the embryo and fetus. In isolated studies, genetic changes, physical development, and morbidity were assessed in children exposed to radiation during the antenatal period. For example, in individuals who underwent in-utero radiation exposure, a clear effect of increased frequency of blood lymphocytes TCR mutations was observed [68]. Moreover, the established patterns of somatic mutagenesis in in-utero exposed individuals persisted 28 years later [69].

In addition, disharmonious physical development was observed in children exposed to in-utero radiation, caused by an age-related increase in the proportion

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[8] Bolshakov LA, ed. Russian National Report: 35 years after the Chernobyl accident. results and prospects of overcoming its consequences in Russia. Moscow: Akadem-Print; 2021 (In Russ.).

of individuals with low body height [70]. However, the dose-response relationship for the radiation exposure effect on the fetus was not assessed.

Due to the significant inconsistency of global data, the incidence of leukemia in individuals exposed to radiation *in utero* was of considerable scientific interest. According to data from the National Radiation and Epidemiological Registry (NRER), no convincing evidence of an increased risk of leukemia development was obtained for children exposed to radiation *in utero* and in early childhood [71]. However, non-cancerous thyroid pathology (most commonly, diffuse non-toxic goiter) was diagnosed more frequently in these children than among non-exposed peers [72, 73]. The incidence rate in children exposed to radiation *in utero* increased sharply with age, reaching a maximum at 7–9 years, and by the age of 12 years decreased to the level observed in non-exposed peers [74, 75]. It is important to note that the observed children, after birth, lived in radiation-contaminated areas (RCA) and, due to consumption of breast milk and cow's milk, were also exposed to postnatal internal radiation. This factor was not taken into account in the study, nor was the level of iodine deficiency in the residential areas before and after the accident.

Thus, the conducted studies did not provide evidence of a link between the health status of children living in RCTc and *in utero* radiation exposure.

CONCLUSION

The analysis of data accumulated over 40 years of follow-up studies involving emergency workers, cleanup workers, and RCT residents has provided crucial new insights into both the early and long-term medical and biological effects of radiation exposure in humans. Among emergency workers, 134 cases of ARS were documented, including 28 fatal cases. New knowledge has been obtained about the pathogenesis, course, and outcomes of ARS in combination with radiation skin damage. The experience gained in diagnosing and treating ARS and its long-term consequences has led to a fundamental revision of clinical tactics and a significant improvement in treatment efficacy for this severe condition, which is characterized by high mortality.

No ARS cases were registered among the cleanup workers who participated in the emergency recovery operations after April 27, 1986, and the population residing in radioactively contaminated territories. The protective measures implemented after the accident (evacuation, establishment of a sanitary protection zone, etc.) significantly reduced radiation exposure levels among the population, remaining well below the threshold dose required to induce ARS.

A comprehensive radiobiological and radiation-epidemiological analysis revealed both preclinical changes, including cytogenetic, molecular genetics-based, and immunological markers, and clinically significant alterations in the health condition of cleanup workers. Radiobiological studies have demonstrated persistently elevated levels of chromosomal aberrations in blood lymphocytes, mutations in genes encoding the T-cell receptor, impairment of T-cell immunity, and an elevated pro-inflammatory cytokine profile in serum.

Regular medical examinations of a large cohort of cleanup workers exposed to a wide range of radiation doses have provided crucial information on the radiation risk of the late effects of prolonged human exposure. A long-term radiation-epidemiological analysis shows that the incidence of leukemia in the first ten years after the accident exceeded the spontaneous level by 32%, and that of cancer and diseases of the cardiovascular system (primarily ischemic heart disease) over the 40-year follow-up period - by 8% and 5%, respectively. The research results support the scientific justification for including aplastic anemia and secondary immunodeficiency states (diseases of the blood and hematopoietic organs) in the Russian list of diseases eligible for inclusion in the list of radiation-related diseases.

Although an increase in the frequency of chromosomal aberrations in blood lymphocytes was observed in the exposed population of contaminated territories in the early period, a comprehensive assessment of the results from 40 years of health monitoring of the RCT population revealed no significant impact of radiation exposure on morbidity rates across all ICD-10 disease classes, except for TC.

According to the latest estimates by NRER specialists, conducted in early 2026, approximately 43% of thyroid cancer cases identified among exposed individuals who were under 18 years of age at the time of the accident are attributable to exposure to ^{131}I. The obtained evidence of the high carcinogenic radiosensitivity of the human thyroid gland to ^{131}I is of crucial importance for improving radiation protection measures for the population. For the first time, it has been demonstrated that chronic, predominantly internal thyroid irradiation in individuals who were children or adolescents at the time of the accident leads to an increased incidence of thyroid cancer 4–5 years after the event.

Analytical study results have established that the radiation risk of cancer from internal exposure to ^{131}I is comparable to the well-studied risk of thyroid cancer following external gamma radiation. However, quantitative estimates of the radiation risk of thyroid cancer remain rather uncertain and require further large-scale and in-depth research to obtain robust and statistically significant results. At the same time, a number of issues related to the TC induction in individuals exposed to radiation before the age of 18 remain relevant. To date, no molecular genetic markers of radiation-induced thyroid cancer have been identified.

It is a cause for concern that 40 years after the Chernobyl accident, an elevated radiation risk of thyroid cancer development still persists among people exposed to radiation during childhood and adolescence in RCTs. In this context, it is extremely important to note that children represent a critical group in terms of thyroid radiation dose during such accidents. Timely implementation of preventive measures — such as early administration of stable iodine, replacement of locally produced cow's milk and meat — can prevent the development of thyroid cancer.

No evidence has been obtained of the impact of parental radiation exposure and *in utero* radiation exposure among RCTs residents on the health status of their descendants. In conclusion, it should be noted that the new radiobiological knowledge gained after the Chernobyl accident is of extremely high importance not only for radiobiology and radiation medicine. Estimates of adverse health effects are already being used today to improve global standards and ensure radiation safety for both occupational workers and the general population.

The authors consider it necessary to acknowledge the significant contribution to the provision of medical care for the affected emergency workers of the Chernobyl Nuclear Power Plant, as well as to the organization of radiation-hygienic and medical monitoring of the health status of Chernobyl accident cleanup workers and the population residing in radioactively contaminated areas, made by the staff of: the State Research Center — Burnazyan Federal Medical Biophysical Center of Federal Biological Agency; the A. Tsyb Medical Radiological Research Centre — branch of the National Medical Research Radiological Centre; the St. Petersburg Research Institute of Radiation Hygiene named after Professor P.V. Ramzaev.

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Authors:

Veronika I. Skvortsova, Dr. Sci. (Med.), Member of RAS, ORCID: https://orcid.org/0000-0003-2815-280X
Andrei D. Karpin, Dr. Sci. (Med.), Professor, Academician of RAS, ORCID: https://orcid.org/0000-0001-8784-8415
Ivan K. Romanovich, Dr. Sci. (Med.), Professor, Academician of RAS, ORCID: https://orcid.org/0000-0003-0668-459X
Igor V. Borisevich, Dr. Sci. (Med.), Professor, ORCID: https://orcid.org/0000-0002-0713-7419
Sergei A. Ivanov, Dr. Sci. (Med.), Member of RAS, ORCID: https://orcid.org/0000-0001-7689-6032
Yury S. Udalov, Dr. Sci. (Med.), ORCID: https://orcid.org/0000-0002-9739-8478
Igor A. Berzin, Dr. Sci. (Med.), ORCID: https://orcid.org/0000-0003-4147-8054
Andrey A. Akleyev, Dr. Sci. (Med.), ORCID: https://orcid.org/0009-0006-2936-2357
Yulia R. Akhmadullina, Cand. Sci. (Biol.), ORCID: https://orcid.org/0000-0003-4394-2228
Evgeniya A. Blinova, Cand. Sci. (Biol.), ORCID: https://orcid.org/0000-0002-2567-7945
Anzhelika A. Bratilova, ORCID: https://orcid.org/0000-0002-6489-3974
Andrey Yu. Bushmanov, Dr. Sci. (Med.), Professor, ORCID: https://orcid.org/0000-0003-1565-4560
Irina A. Galstyan, Dr. Sci. (Med.), ORCID: https://orcid.org/0000-0002-7571-971X
Victor K. Ivanov, Dr. Sci. (Tech.), Professor, Member of RAS, ORCID: https://orcid.org/0000-0003-1372-0018
Michail V. Konchalovsky, Cand. Sci. (Med.), ORCID: https://orcid.org/0000-0003-0812-4596
Olga S. Kravtsova, Cand. Sci. (Biol.), ORCID: https://orcid.org/0009-0008-5543-5411
Irina S. Kuznetsova, Cand. Sci. (Biol.), ORCID: https://orcid.org/0000-0002-1214-295X
Marat A. Maksioutov, Cand. Sci. (Tech.), ORCID: https://orcid.org/0000-0001-7229-0092
Nelya A. Metlyaeva, Dr. Sci. (Med.), ORCID: https://orcid.org/0000-0003-3863-8424
Svetlana F. Sosnina, Dr. Sci. (Med.), ORCID: https://orcid.org/0000-0003-1553-0963
Yulia V. Tsareva, Cand. Sci. (Med.), ORCID: https://orcid.org/0000-0001-5559-4457
Sergey Yu. Chekin, ORCID: https://orcid.org/0000-0002-6759-868X
Sergey M. Shinkarev, Dr. Sci. (Tech.), ORCID: https://orcid.org/0000-0003-0844-4733
Olga V. Shcherbatykh, ORCID: https://orcid.org/0000-0002-6071-8984
Lubov A. Yunanova, ORCID: https://orcid.org/0000-0001-6858-9219
Alexander V. Akleyev, Dr. Sci. (Med.), Professor, ORCID: https://orcid.org/0000-0003-2583-5808