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The Journal is in the leading scientific journals of the Supreme Examination Board (VAK), RSCI and Scopus



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*Original article*


# STATE SCIENTIFIC CENTER OF THE RUSSIAN FEDERATION — FEDERAL MEDICAL BIOPHYSICAL CENTER NAMED AFTER A.I. BURNAZYAN OF FMBA OF RUSSIA: 75 YEARS ON GUARD OF PEOPLE'S HEALTH

A.S.Samoylov[1], A.Yu.Bushmanov[1], S.F.Goncharov[1,2]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation
[2] Russian Medical Academy of Continuous Professional Education, the Ministry of Health of the Russian Federation, Moscow, Russian Federation

**Abstract.** The article presents the history of creation, formation and development of the State Scientific Center of the Russian Federation — Federal Medical Biophysical Center named after A.I. Burnazyan of the Federal Medical and Biological Agency of Russia (A.I. Burnazyan Federal Biophysical Center, the Center). The Institute of Biophysics of USSR Ministry of Health and Clinical Hospital № 6, predecessors of the Center, were engaged in the elimination of medical and sanitary consequences of Chernobyl Radiation Accident (1986). The main directions of activities of the A.I. Burnazian Federal Medical Biophysical Center — the flagship institution of Russian health care in the field of biophysics, radiation and nuclear medicine are considered. The perspectives of scientific activity of the Center related to solving actual problems of modern radiobiology, radiation safety and biomedical technologies are outlined. It is concluded that it is expedient to create the Disaster Medicine Service of the Federal Medical and Biomedical Agency of Russia.

**Keywords:** *A.I.Burnazyan Federal Medical Biophysical Center, biophysics, Chernobyl accident, Emergency Medicine Service of FMBA of Russia (project), emergency response, emergency situations, Federal Medical and Biological Agency (FMBA of Russia), nuclear medicine, radiation safety, radiation accidents, radiobiology*

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***Оригинальная статья***


# ГОСУДАРСТВЕННЫЙ НАУЧНЫЙ ЦЕНТР РОССИЙСКОЙ ФЕДЕРАЦИИ – ФЕДЕРАЛЬНЫЙ МЕДИЦИНСКИЙ БИОФИЗИЧЕСКИЙ ЦЕНТР ИМЕНИ А.И.БУРНАЗЯНА ФМБА РОССИИ: 75 ЛЕТ НА СТРАЖЕ ЗДОРОВЬЯ ЛЮДЕЙ

А.С.Самойлов[1], А.Ю.Бушманов[1], С.Ф.Гончаров[1,2]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия
[2] ФГБОУ ДПО «Российская медицинская академия непрерывного профессионального образования» Минздрава России, Москва, Россия

**Резюме.** Представлена история создания, становления и развития Государственного научного центра Российской Федерации – Федерального медицинского биофизического центра имени А.И.Бурназяна ФМБА России (ФМБЦ им. А.И.Бурназяна, Центр). Отмечено, что особой страницей в деятельности Института биофизики Минздрава СССР и Клинической больницы №6 – предшественников ФМБЦ им. А.И.Бурназяна – является работа по ликвидации медико-санитарных последствий радиационной аварии (РА) на Чернобыльской АЭС (1986). Рассмотрены основные направления деятельности ФМБЦ им. А.И.Бурназяна – флагманского учреждения российского здравоохранения в области биофизики, радиационной и ядерной медицины. Намечены перспективы научной деятельности Центра, связанные с решением актуальных вопросов современной радиобиологии, радиационной безопасности и биомедицинских технологий. Сделан вывод о целесообразности создания Службы медицины катастроф ФМБА России

**Ключевые слова:** *аварийное реагирование, авария на Чернобыльской АЭС, биофизика, радиационная безопасность, радиационные аварии, радиобиология, Служба медицины катастроф ФМБА России (проект), Федеральное медико-биологическое агентство (ФМБА России), Федеральный медицинский биофизический центр им. А.И.Бурназяна, чрезвычайные ситуации, ядерная медицина*

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***Contact information:***
***Andrey Yu. Bushmanov*** – Dr. Sc. (Med.), Prof.; Deputy Director General
**Address:** 46, Zhivopisnaya str., Moscow, 123098, Russia
**Phone:** +7(964)-725-32-04
**E-mail:** radclin@yandex.ru

***Контактная информация:***
***Бушманов Андрей Юрьевич*** – доктор медицинских наук, профессор; первый заместитель генерального директора
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, д. 46.
**Тел.:** +7(964)-725-32-04
**E-mail:** radclin@yandex.ru

In 2021, the State Scientific Center of the Russian Federation — Federal Medical Biophysical Center named after A.I. Burnazyan of FMBA of Russia (hereinafter - the Center, FMBC named after A.I. Burnazyan) celebrates its 75th anniversary. Over the years, the Center has repeatedly proven its high competence in nuclear medicine, radiation safety, radiobiology, and emergency response.

In May 1946, a radiation laboratory was established on the initiative of A.I. Burnazyan. Its purpose was to study the effect of radiation on the human body and to develop possible means of treatment and protection against the radiation factor. At that time the need for scientific substantiation of radiation safety norms and rules, maximum permissible doses and maximum concentrations of various toxic substances, as well as the study of early specific signs and clinics of new occupational diseases and poisonings caused by radioactive substances was maturing.

To solve these problems, in August 1947, in accordance with the Decree of the Council of the USSR Ministry of Health, the Third Main Directorate (now the Federal Medical and Biological Agency, FMBA) was established under the USSR Ministry of Health. Its system included special research institutes to study the effects of radiation and other physical and chemical factors on the human body. It also included medical-sanitary units for treatment and rehabilitation of victims of radiation and of other physical factors.

*Clinical Hospital of the Moscow Health Department No. 6.* On the initiative of A.I. Burnazyan, in accordance with the Order of the Ministry of Health of the USSR from September 25, 1948 № 14 on the basis of the Moscow Neurosurgical Hospital for the disabled of World War II a closed type clinical hospital was created. The patients of the hospital were the employees of institutions and enterprises of nuclear power industry. Later the hospital was transferred to the jurisdiction of the Third Main Directorate of the USSR Ministry of Health.

*Medical-Sanitary Unit No.12.* In May 1948 on the basis of order of A.I. Burnazyan a medical-sanitary unit [1]12 was organized on the territory of I.V. Kurchatov Institute on the basis of a small outpatient clinic of 7 doctors' offices. Doctors and medical personnel of the medical unit served the personnel of the Russian Research Center “Kurchatov Institute”, Institute of High-Technology Scientific Research of Inorganic Materials named after A.A. Bochvar, the Research Institute of Instrument Engineering, the Institute of Biophysics of USSR Ministry of Health, as well as the residents of nearby areas. In 2004, the medical unit №12 was transformed into Clinical Hospital №86 of the Federal Medical and Biological Agency of Russia.

*Institute of Biophysics of the USSR Ministry of Health.* In 1948 the Institute of Biophysics of the Ministry of Health of the USSR was established on the basis of a radiation laboratory. The work of a large team of hygienists resulted in several editions of state radiation safety standards and basic sanitary rules to ensure radiation safety. The team edited more than a hundred monographs, thousands of articles, a set of sanitary norms and rules, hygienic standards, regulatory and methodological documents on all areas of radiation safety of personnel and population and on all facilities of the nuclear fuel cycle.

*The Chernobyl accident is a special page in the history of the Institute of Biophysics and Clinical Hospital No. 6.*

Since April 1986 dozens of specialists in radiation hygiene and personnel safety have directly participated in Chernobyl accident consequences elimination. On December 19, 1994 the Institute of Biophysics was granted the status of the State Scientific Center of the Russian Federation.

In the first hours after the catastrophe, scientists, doctors, and specialists from emergency teams arrived at Chernobyl and organized medical triage and medical evacuation of the most severely injured to Clinical Hospital No. 6. There they were provided with medical care. Also, necessary complex studies on exposure assessment using methods developed by the staff of the Institute were performed. The Institute specialists provided scientific and methodological guidance to radiation safety services. Their contribution concerned the issues of individual dosimetry, decontamination, organization of individual personnel protection, psychophysiological support, etc. As a result valuable scientific data were obtained. Their analysis and generalization allowed to develop practical recommendations on prevention of radiation accidents and on improvement of preparedness of emergency rescue teams to eliminate consequences of probable radiation accidents.

Today, the Burnazyan Federal Biomedical Center is the flagship institution of Russian health care in the field of biophysics, radiation and nuclear medicine. The Center's scientific activities are focused on the development of biomedical and additive technologies, radiopharmaceuticals, radiation monitoring and dosimetry. The Center performs scientific research work under the state defense order, federal target programs, cooperation with SC "Rosatom" and international organizations in its field of activity. In 2020 the Center was included in the National Project "Science" with a project to create a center for additive technologies. These developments, implemented in clinical practice, will be a big step forward in the development of Russian health care.

The Center has a multidisciplinary clinic with an annual capacity of 20,000 patients. The clinic provides specialized, including high-tech, medical care to the assigned contingent, as well as to all those in need of quality medical care. The assigned contingent includes employees of nuclear industry enterprises and athletes of the Russian Federation national teams.

The Center's educational activities are determined by the state's tasks to ensure safe living conditions for the Russian population. At the forefront of this work is the Medical-Biological University of Innovation and Continuing Education of FMBA of Russia. As in all leading institutions of higher education, during the COVID-19 pandemic, the University did not cease its educational activities, and its thesis defense took place online.

Together with Rosatom and FMBA specialists, scientists from the Center regularly take part in educational and training events. They practice actions to eliminate consequences of radiation emergencies.

The Center conducts research in the field of molecular, biochemical and genetic mechanisms of radiation lesion formation and postradiational recovery. One of them is treatment of local radiation lesions with mesenchymal stem cells combined with microsurgical technique. This method showed good results in the experiment.

During the peak of the pandemic of the new coronavirus infection COVID-19, the Center continued to provide routine medical care. In 2020, for the first time in Russia, the Center used a unique technology of Salvage liver transplantation — staged liver transplantation for primarily unresectable tumors. The Center has the largest experience of liver transplantation for oncological and parasitic pathologies in the country. Since 2010 the Center has performed more than 400 transplants.

An important area of activity of the A.I. Burnazyan Federal Medical and Biological Center of the Federal Medical and Biological Agency of Russia is active participation in the implementation of medical and social policy to improve and to develop the system of protection, life saving and health preservation of victims of emergency situations. This applies both to workers in certain areas of the economy with particularly hazardous working conditions, and to the population of certain territories of the Russian Federation served by FMBA of Russia.

Specialists at the Russian Federal Medical and Biological Agency, including the A.I. Burnazyan Federal Medical and Biological Center, solve specific tasks of medical-sanitary and medical-biological support of employees of special facilities and territories of importance to the country's economy and security. One of the peculiarities of these facilities is that they are widely dispersed throughout the country, including border regions.

In addition, the Center and other medical organizations of FMBA of Russia are tasked with the medical support of work to localize and to eliminate medical and sanitary consequences of terrorist acts. Terrorist acts may involve radioactive substances, highly toxic chemical compounds, and biological agents. Thus the given socially dangerous phenomena can arise in various territories. Including the territories of closed administrative-territorial formations and the settlements located in them. Such conditions require the use of special technologies for organization and implementation of medical care, as well as their continuous improvement, taking into account the development of medical science and health care practice.

In conditions of hybrid warfare, facilities and territories serviced by FMBA of Russia may become priority targets for terrorist attacks or high-precision weapons strikes. It is very likely that several emergency zones will arise — simultaneously or within a short period of time — foci of human destruction, disruption of life support systems, complete or partial failure of some medical and other medical organizations that provide medical and biomedical support to facility employees and the population living in these territories.

Sufficient medical forces and means are available to eliminate medical and sanitary consequences of probable emergencies at the facilities and territories currently serviced by the Center and — in general — by the Agency. Their dislocation is justified taking into account the specifics of tasks of medico-sanitary and medico-biological support of special facilities and territories.

The organization and provision of medical assistance to victims in emergency situations is carried out in medical treatment organizations (medical-sanitary units, clinical hospitals, centers). They are usually located in the immediate vicinity of organizations and enterprises with particularly hazardous working conditions. The system of providing emergency medical aid and of organizing measures for timely liquidation of medical and sanitary consequences of accidents is built taking into account the specifics of the main production, in close interaction with the relevant services of industrial ministries, organizations and enterprises, regional health care, institutions and formations of the All-Russian Disaster Medicine Service.

In order to maintain the readiness of management bodies and medical organizations of FMBA of Russia to respond and to act in emergency situations, a system of operational duty officers has been created and is functioning. There is round-the-clock duty and interaction. This includes participation in operational meetings led by the National Center for Crisis Management of EMERCOM of Russia and the National Defense Management Center of the Russian Federation held via videoconferencing.

In addition, a system for monitoring possible radiation, chemical and biological threats that could lead to medical and sanitary consequences has been created and is being developed. The system also monitors the condition of victims, their need for consultations, including telemedicine, and monitors medical evacuations. The technologies of collecting, summarizing and analyzing the relevant information are perfected. The results of monitoring allow us to quickly obtain the necessary information to make more informed decisions.

To improve the readiness of the Center, as well as of other management bodies and medical organizations of FMBA of Russia to respond and to take adequate actions in case of the most probable emergencies of radiation, of chemical and biological nature at the facilities and territories serviced by the Agency — a comprehensive work on creating multiple scenarios of response to such emergencies and training on their implementation is carried out. Relevant leading specialists are involved in this work.

In order to improve the system of organization and provision of medical care and medical evacuation, specialists of the Center and of other FMBA organizations are working to optimize the routing of medical evacuation of patients and casualties in emergency situations. For example, in September 2021, specialists from medical organizations will take part in an interdepartmental scientific and practical exercise conducted by the Ministry of Emergency Situations of Russia in the Arctic zone of the Russian Federation. They will also participate in the development of the Universal Integrated Rescue Center project to support the activities of rescuers in the Arctic.

Every year, the work of the automated information and telecommunication system, which functions around the clock in the interests of disaster medicine, is improved. Currently, 209 medical organizations of the Agency are connected to the federal segment of the Telemedicine System, and their number will grow.

In 2020, specialists of medical institutions of the Federal Medical and Biomedical Agency of Russia conducted 924 telemedicine consultations at the federal level, and in five months of 2021 over 1.6 thousand telemedicine consultations were performed, including by medical specialists of the Center. These data show that the FMBA of Russia has created, actively operates and develops a system for organizing and conducting telemedicine consultations.

In order to organize telemedicine consultations for victims of emergencies, the collection and processing of operational reports on emergencies using the information system "Operational reports on the progress of medical and sanitary consequences of emergencies in the FMBA of Russia" was organized.

At present, the Center and other medical organizations of the Federal Medical and Biological Agency of Russia are implementing a set of measures to develop the system of medical care for victims of emergencies. These measures cover not only the clinical base, medical-sanitary units, hospitals and centers, but also mobile medical formations, and also include the training of medical personnel in disaster medicine. In particular, a modern mobile field hospital is being formed on the basis of the Center. The necessary conditions and facilities will be created in it for performing the most informative diagnostic examinations and obtaining in a short time the relevant data on the condition of the victims. This will make it possible to provide them with adequate medical aid, first of all, in emergency and urgent forms, and to prepare them for further medical evacuation to designated medical treatment facilities.

The creation of mobile medical formations with dual purpose is carried out taking into account their purpose, and also taking into account the requirements for specialists trained to provide emergency, including specialized emergency, medical care and disaster medicine; the requirements for modern treatment and diagnostic complexes, devices and appliances, medical and other types of necessary equipment. One of the important requirements is the ability to deliver these formations to the area of application not only by road, but also by air transport.

In addition, together with scientists from Lomonosov Moscow State University, work was done to improve medical evacuation vehicles — portable transportable isolated robotic medical evacuation complexes.

The practice of involvement of medical formations and organizations of FMBA of Russia in the elimination of medical and sanitary consequences of emergencies such as the catastrophic flooding in Krasnodar Region (2012), flooding in the Far East (2013), the Georgian-South Ossetian armed conflict (2008), pandemic of the new coronavirus infection and others, shows: the management and coordination of forces and means when working in modes of daily activity and emergency — needs to be improved.

The results of the analysis of the multidisciplinary work to eliminate medical and sanitary consequences of various emergencies, including terrorist acts and local armed conflicts, convince us that it is advisable to create a Disaster Medicine Service (hereinafter, the Service) within the FMBA of Russia.

This conclusion fully agrees with the decision of the meeting of the Government Commission for the Prevention and Elimination of Emergency Situations and Ensuring Fire Safety. According to this decision it was recommended to FMBA of Russia to study the issue of establishment of the Disaster Medicine Service of FMBA of Russia and — in case of positive decision — to amend regulatory legal acts of the Russian Federation governing the establishment and functioning of the All-Russian Disaster Medicine Service — a subsystem of the Unified State System for Prevention and Liquidation of Emergency Situations — Minutes of March 19, 2021, p.1, IV.

The practical work of the All-Russian Disaster Medicine Service in organizing and providing medical aid to victims and their medical evacuation in emergency situations confirms the correctness of the basic conceptual provisions adopted at its creation, as well as the feasibility of the organizational structure created. In the state reports on the state of protection of population and territories of the Russian Federation from emergencies of natural and man-made character, this subsystem was repeatedly noted as the most effective in the framework of the RSChS.

The creation of the Service will make it possible to functionally unite the medical forces and means of the Federal Medical and Biological Agency of Russia into a single system. First of all, the forces and means of constant readiness of the federal level, designed to eliminate medical and sanitary consequences of emergencies. Due to the implementation of such an organizational decision, there will be an increase in the efficiency of response to emergencies, the level of guaranteed life-saving and health preservation of victims in emergencies at the facilities and territories served by the Center and the entire FMBA of Russia, not only in peacetime, but also in wartime.

In addition, the establishment of the Service will improve the quality of management activities in the field of disaster medicine, the quality of work of the medical treatment organizations subordinated to the Agency on issues of interaction with health authorities and relevant medical treatment organizations of the subjects of the Russian Federation, as well as with medical services and organizations of other federal executive bodies deployed in the territories of regions — in the interests of eliminating medical and sanitary consequences of emergencies

With the presence of the Service there will be created conditions: for systematic generalization of experience of preparation of medical forces and means for response and actions in emergency situations; for organization and performance of the most significant scientific works; for more targeted professional training of medical personnel involved in liquidation of medical and sanitary consequences of emergencies, on disaster medicine; for monitoring of their competences and professional growth, as well as of condition and development of regulatory, educational, methodical and material base.

*Prospects for the scientific development of the Center are related to the solution of the following topical issues of modern radiobiology, radiation safety and biomedical technologies.*

Search for markers of radiation injury, radiotolerance of cells, tissues and organism, risk of distant effects of radiation; development of diagnostic methods and prognostic criteria for the tasks of radiation medicine. Development of means and methods for prevention and treatment of radiation injuries. Preclinical studies of counterradiation synthetic and natural substances for different scenarios of radiation exposure — radiation accidents, accidents at atomic productions, radiation diagnostics and therapy, space flights. Study of mechanisms of formation of molecular and cellular effects of ultra-short pulse and dense-ionizing radiation. Development of approaches to decrease the radioresistance of human tumor stem cells.

Further research on the diagnosis and treatment of human radiation injuries with combined lesions (trauma, gamma-neutron damage with RW contamination) using a unique information resource — acute radiation disease database to analyze dose-time-effect relationships for various conditions of uniform and non-uniform accidental exposure.

Development and implementation of technologies to extend the working life of highly qualified employees of the nuclear industry, including search and application of effective health improvement programs that increase the level of psychophysiological adaptation of the personnel of particularly hazardous industries.

Maintaining the readiness of the emergency response and medical and sanitary support system of FMBA of Russia during radiation accidents and at the stages of radioactive waste and spent nuclear fuel management. Improving the system of emergency response and medical and sanitary support, including in the Arctic zone of the Russian Federation.

To conduct comprehensive radiation and hygienic monitoring of the environment and the state of health of the population living in the regions where nuclear power plants and other radiation hazardous facilities are located and in the areas of nuclear and uranium legacy.

Medico-hygienic assessment of the impact of work on the handling of new advanced fuels on the environment and on the health of the population living in the areas of the enterprises involved in the industrial production of such fuel.

Medical and hygienic safety of work with rocket fuel components at Baikonur and Vostochny cosmodromes.

Expertise in medical nuclear forensics.

Ensuring qualitative performance of comprehensive radiation and hygienic studies at the enterprises of the nuclear weapons complex of the State Company "Rosatom". Development of scientific research to ensure radiation safety of personnel during the manufacture and handling of new types of nuclear fuel for NPPs in the "Breakthrough" project area. Active participation in working groups to harmonize Russian legal and regulatory and methodological documents with international recommendations of the International Commission on Radiological Protection and the International Atomic Energy Agency — IAEA (2021-2022). Use of voxel-phantom technology to solve problems of emergency dosimetry and optimization of radiation protection.

Establishment at the Burnazyan Federal Medical and Biological Center of Medical and Biological Research of special traumatic agents and of non-ionizing radiation factors.

In the field of nuclear medicine — commissioning of TR-24 cyclotron will allow a breakthrough expansion of the range of radionuclides and radiopharmaceuticals based on them. Development of polyvalent radiopharmaceuticals with 44Sc, 64Cu, 68Ga for diagnosing both oncological (folate, FAPI, sialic acid) and non-oncological pathologies, including pathologies of cardiovascular system (stenosis, thrombosis), chronic obstructive pulmonary disease, rheumatoid arthritis etc. Development of the concept of theranostic radiopharmaceuticals on the basis of 68Ga/177Lu, and later — 44Sc/47Sc and 64Cu/67Cu. Development of the concept of application of radiopharmaceuticals on the basis of labeled monoclonal antibodies for diagnostics (64Cu, 89Zr) and therapy (90Y, 177Lu). Development of radiopharmaceuticals for radionuclide therapy on the basis of alpha-emitting radionuclides (212Pb, 225Ac, 227Th ...). Development and testing of new generators (68Ge/68Ga, 44Ti/44Sc), which meet the world standards, with the potential registration as medical devices. Optimization of the finished dosage form of 177Lu based therapeutic radiopharmaceuticals for therapy of prostate cancer (ligands for PSMA) and other malignant neoplasms. Development of research in the field of three-dimensional dosimetry systems, proton-capture neutron-capture therapy using 11B, Gd and 10B.

As part of the regenerative medicine development program at FMBA of Russia — to carry out scientific justification, development and production of a biomedical cellular product based on a clean room complex according to GMP-standards ISO-5. Creation of volumetric cell-based models using 3D-printing (bioprinting). Development of technology for obtaining pancreatic islet cells for further transplantation to patients with severe decompensated diabetes. Development of new methods of autoimmune diseases treatment (scleroderma, psoriasis, alopecia, etc.) using regenerative medicine principles.

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**Original article**


# ISSUES OF SCIENTIFIC SUPPORT OF RADIATION SAFETY BASED ON THE EXPERIENCE OF OVERCOMING THE CONSEQUENCES OF THE CHERNOBYL ACCIDENT

Yu.E.Kvacheva[1], N.K.Shandala[1], O.V.Parinov[1], E.G.Metlyaev[1], A.O.Lebedev[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** The measures on liquidation of the Chernobyl accident consequences are analyzed from the point of view of topical issues of ensuring radiation safety of the personnel of radiation hazardous facilities and the population.
The following problems have been considered: organization of liquidation of medical and sanitary consequences and rendering medical aid to victims of the Chernobyl accident; radiation hygienic standardization, control and monitoring; improvement of emergency response system; development of new medical technologies for treatment of acute radiation disease and local radiation injuries; application of radiation protective drugs. It is stated that the experience of liquidation of the Chernobyl accident consequences created a scientifically grounded base for the work on further improvement of the radiation safety assurance system with fixation of the main provisions in the existing regulatory documents.
Conclusions are drawn about the expediency of:
- development of new medical and sanitary technologies aimed at ensuring radiation safety;
- completion of a unified system of response and protection in the event of radiation accidents;
- further search and development of methods and means of prevention and treatment of human radiation pathology, including innovative biomedical technologies;
- improving the methodology for studying the consequences of radiation exposure of the personnel of radiation hazardous facilities and the population;
- development of a new scientific field — medical nuclear forensics.

**Key words:** *legal framework, medical examinations, nuclear industry personnel, psychophysiological examination, radiation accidents, regulatory documents*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***


# ВОПРОСЫ НАУЧНОГО ОБЕСПЕЧЕНИЯ РАДИАЦИОННОЙ БЕЗОПАСНОСТИ НА ОСНОВЕ ОПЫТА ПРЕОДОЛЕНИЯ ПОСЛЕДСТВИЙ ЧЕРНОБЫЛЬСКОЙ АВАРИИ

Ю.Е.Квачева[1], Н.К.Шандала[1], О.В.Паринов[1], Е.Г.Метляев[1], А.О.Лебедев[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России Москва, Россия

**Резюме.** Рассмотрены проблемы: организации ликвидации медико-санитарных последствий и оказания медицинской помощи пострадавшим при Чернобыльской аварии; радиационно-гигиенического нормирования, контроля и мониторинга; совершенствования системы аварийного реагирования; разработки новых медицинских технологий лечения острой лучевой болезни и местных лучевых поражений; применения радиозащитных препаратов. Констатировано, что опыт ликвидации последствий аварии на Чернобыльской АЭС создал научно-обоснованную базу для работы по дальнейшему совершенствованию системы обеспечения радиационной безопасности с закреплением основных положений в действующих регулирующих документах.
Сделаны выводы о целесообразности:
– разработки новых медико-санитарных технологий, направленных на обеспечение радиационной безопасности;
– завершения создания единой системы реагирования и защиты в случае радиационных аварий;
– дальнейшего поиска и разработки методов и средств профилактики и лечения лучевой патологии человека, включая новые инновационные биомедицинские технологии;
– совершенствования методологии изучения последствий облучения персонала радиационно опасных объектов и населения;
– развития нового научного направления – медицинской ядерной криминалистики.

**Ключевые слова:** *аварийное реагирование, авария на Чернобыльской АЭС, защитные мероприятия, лечение пострадавших, медицинская ядерная криминалистика, радиационная безопасность персонала и населения, радиационная медицина, радиационно-гигиеническое нормирование*

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***Contact information:***
***Nataliya K. Shandala*** – Dr. Sc. (Med.); Science and Biophysics Technologies Deputy Director General
**Address:** 46, Zhivopisnaya str., Moscow, 123098, Russia
**Phone:** +7(499)190-93-29
**E-mail:** shandala-fmbc@bk.ru

***Контактная информация:***
***Шандала Наталия Константиновна –*** доктор медицинских наук; заместитель генерального директора по науке и биофизическим технологиям
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, д. 46.
**Тел.:** +7(499)190-93-29
**E-mail:** shandala-fmbc@bk.ru

On April 26, 1986, a tragedy occurred that had significant medical and sanitary consequences — the accident at the Chernobyl nuclear power plant (ChNPP). It changed the course of nuclear power development, forced to reconsider approaches to ensuring safety of nuclear power installations and to ensuring radiation safety of personnel and population. Although 35 years have already passed since the accident, we vividly remember the events of those tragic days. We remember how heroically, sometimes at the cost of own lives, the elimination of its consequences was organized from the first hours of the accident.

The Third Main Directorate under the USSR Ministry of Health (hereinafter referred to as the Third Main Directorate) was directly involved in the liquidation of the Chernobyl accident consequences. Later it will be transformed into the Federal Medical and Biological Agency (FMBA of Russia).

17 minutes after the accident the Third Main Directorate received operational information about the first 18 people affected (Fig. 1).

From that moment on, an operational system of emergency response came into effect. The Operational Headquarters for the coordination of medical specialists began its work.

An emergency team from the Institute of Biophysics and the 6th Clinical Hospital of the Third Main Directorate (now the Burnazyan Federal Medical Biophysical Center) arrived in Pripyat at 14:30, 13 hours after the accident. The team included radiologists, hygienists, dosimetrists and other specialists. They had special packs with dosimetric equipment, medicines, and reagents. More than 100 affected people were in the hospital of the Chernobyl medical and sanitary unit by that time, and they continued to arrive.

Physicians-hygienists and dosimetrists from the Institute of Biophysics evaluated the radiation situation. By 19:00 they formulated a scientific justification and made a proposal. The question was about evacuation of population, first of all pregnant women and children, from the 50-thousand-strong town of Pripyat. The main tasks of clinical group were examination and carrying out of medical triage of the victims. At this stage alone, in the first 24 hours after the catastrophe the members of the emergency team performed over one thousand blood analyses and formed a group for the evacuation of the injured (evacuation group — 129 persons) to the clinic of the Institute of Biophysics.

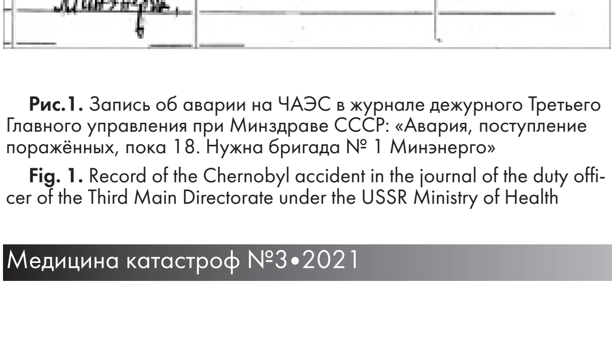

**Рис.1.** Запись об аварии на ЧАЭС в журнале дежурного Третьего Главного управления при Минздраве СССР: «Авария, поступление поражённых, пока 18. Нужна бригада № 1 Минэнерго»

**Fig. 1.** Record of the Chernobyl accident in the journal of the duty officer of the Third Main Directorate under the USSR Ministry of Health

Medical specialists urgently conducted therapeutic, preventive and radiation-hygienic measures, performed individual dosimetric control, determined and evaluated exposure dose rates, determined the radius of the site beyond which the development of radiation sickness was excluded, etc. Besides, they participated in specification of indications for urgent evacuation of the population of Pripyat and nearby settlements, radiation monitoring and other protective measures. Treatment hospitals and polyclinics were additionally deployed in the 30-km zone. The personnel were provided with medical equipment, instruments and medicines.

In the first days after the accident, the focus was on providing qualified medical aid to the casualties. The first plane with 84 casualties arrived in Moscow on the morning of April 27. In the evening of the same day, a special flight brought another 45 people to Moscow.

The diagnosis of acute radiation sickness was confirmed in 108 patients of the clinic of the Institute of Biophysics of the USSR Ministry of Health. Almost one third of them had a severe (III) and extremely severe (IV) degree of the disease. Thanks to the efforts of our doctors, it was possible to save the lives of several patients with severe forms of the disease, including one who had received an absolutely fatal dose (Fig. 2).

With the initially predicted level of lethality — more than 40 affected people — medical losses in the acute period (within 4 months after the accident) amounted to 27 people. Thus, the largest number of cases of acute radiation sickness — 134 — occurred as a result of the Chernobyl accident. This is in comparison to the number of cases of acute radiation sickness resulting from all radiation accidents and incidents. Two contingents are considered: witnesses to the accident and firemen. No cases of acute radiation sickness were detected among the so-called liquidators (people involved in emergency works at Chernobyl NPP and in the 30-km zone), as well as among the population living in areas of radioactive contamination. The Burnazyan Federal Medical and Biological Center clinic, based at the former Clinical Hospital No. 6, has a long-term, lifelong, follow-up of a group of persons who suffered acute radiation sickness [2, 3].

Describing the overall activity of the staff of the Institute of Biophysics during these difficult days, it is difficult to refrain from stressing the word "first time". For the first time the medical institution was faced with a simultaneous admission of such a significant number of patients with acute radiation sickness. The Chernobyl group was almost half the total number of those who suffered acute radiation sickness as a result of all accidents in our country in the previous 40 years of the nuclear project.

On the eve of the accident the clinic of the Biophysics Institute had 120 beds and two sterile wards, occupying two floors in Clinical Hospital No.6. When the scale of the arrival became evident, the hospital departments were reassigned. A total of 11 new clinical departments were formed, including a dedicated blood and bone marrow donor unit. In fact, the work of medical personnel was approximated to that of the medics in the front-line hospitals. The patients evacuated from the accident site required constant monitoring and care. Doctors and nurses worked as hard as they could, resting 3-4 hours a day without leaving the clinic.

For the first time it was necessary to organize mass reception of patients with high levels of radioactive contamination. According to the dosimetrists, the "dirt" was such that the dosimeters were "off the scale", detecting a 1000-fold excess of the radiation background. In the wards during the first days the gamma radiation dose rate reached values of the order of several mR/h.

For the first time in the world, therapy with hematopoietic growth factors ("cytokine therapy") was used to treat acute radiation sickness in Chernobyl victims. The experience of allogeneic stem cell transplantation was also significantly enriched. It was at the clinic of the Institute of Biophysics that the first bone marrow transplantation in our country was performed in January 1975. Hematopoietic stem cell transplantation was performed in 19 cases during the treatment of Chernobyl victims. This is about 2/3 of the worldwide experience of transplantation therapy in patients with acute radiation sickness.

For the first time, real successes were achieved in the treatment of radiation burns. In 11% of Chernobyl patients the burn area exceeded 50% of the total body surface area, in 30% of patients it was from 10 to 50%. The treatment of such patients posed special difficulties. "Lioxazole" played an important role in the complex treatment of burns. The knowledge obtained in the management of Chernobyl burn patients formed the basis of modern regenerative medicine, a field that is now successfully developing at the A.I. Burnazyan Federal Medical and Biological Center.

**Рис.2.** Врачи и пациенты клинической больницы №6 Третьего Главного управления при Минздраве СССР в апреле-июне 1986 г.

**Fig. 2.** Doctors and patients of Clinical Hospital No. 6 of the Third Main Directorate of the USSR Ministry of Health in April-June 1986

**Рис.3.** Работа специалистов Института биофизики Третьего Главного управления при Минздраве СССР в Чернобыле в 1986-1987 гг.
**Fig. 3.** The work of specialists from the Institute of Biophysics of the Third Main Directorate of the USSR Ministry of Health in Chernobyl in 1986-1987

For the first time in the world, our specialists conducted detailed clinicopathological studies of acute respiratory distress syndrome in radiation patients. The experience of these studies turned out to be in demand during the COVID-19 pandemic.

In the future, the work was based on the rotation method — 40-80 specialists were sent to the work area every month. Scientists and engineers of the Biophysics Institute developed normative-methodical documents in the shortest possible time. They established specific norms and rules for elimination of the consequences of a large-scale radiation accident in conditions of a complicated radiation situation. More than 2,000 specialists from the institutions of the Third Main Directorate were involved in organizing and carrying out measures to eliminate the consequences of the Chernobyl accident (Fig. 3).

In the acute period of the accident, our specialists made a forecast of possible long-term consequences in the form of oncological morbidity among the population. It showed an extremely low probability of radiation-induced leukemia and solid cancers, except for an expected increase in the number of malignant thyroid tumors among the child population. One year after Chernobyl, a seminal report on the problem was sent to the United Nations Scientific Committee on the Effects of Atomic Radiation. This is the world's most authoritative scientific body in this field. In its report to the UN General Assembly in 1988, the Committee evaluated the work of our medical scientists as follows: "The information presented by the USSR is exhaustive and very valuable. The Committee considers that it is indebted to all the authors for their readiness to share their experience and wishes to acknowledge their professional skill and human compassion shown in connection with such tragic circumstances".

*New normative and methodological documents.* The scale of the Chernobyl accident and the complexity of the radiation situation required prompt development of additional norms and rules for their implementation. As a result of the accident, the territory of the European part of the USSR with an area of about 150 000 km$^2$ , where about 6 million people lived, was subjected to radioactive contamination - within the isoline of 1 Ci/km$^2$ or 37 kBq/m$^2$ . In the shortest possible time it was necessary to solve the problem of development of a scientifically substantiated strategy of state actions to protect the population. Within two weeks after the catastrophe a group of our scientists under the scientific leadership of academicians L.A. Ilyin and Yu. A. Izrael developed Recommendations on criteria of residence possibility of population on the Chernobyl contaminated territory, necessity of their resettlement and temporary evacuation (further referred to as Recommendations). In this document approved on May 22, 1986 there were established emergency exposure limits for the population — 100 mSv for the first year after the accident (with subsequent decrease of this value). Zoning of the territories according to the levels of gamma-radiation on the ground was carried out for the first time. In the zones with high levels of radioactive contamination — in the so-called 'tight control zones' where dose loads on people could exceed 100 mSv/year without taking measures for restricting their vital activity — there were 273 000 people living in 789 populated settlements. According to the Recommendations life activity restrictions were introduced in these areas. These were: a ban on the consumption of milk and local foodstuffs with their replacement by "clean" products; predominant stay of people in buildings rather than in the open air, etc. As a result, it was possible to reduce the dose load by a factor of 3 as compared to the established regulations [4].

Ensuring radiation safety of the population living in areas of radioactive contamination required the development of permissible levels of internal exposure in the form of permissible concentrations of long-lived radionuclides in a variety of objects: fodder, milk, meat, grain products, drinking water, clothing, medicinal plants, vehicles, etc. Thus, specialists of the Institute of Biophysics in the shortest possible time developed more than 30 regulatory and methodological documents. Among the first regulatory documents were the Temporary Permissible Content of Iodine-131 in potable water and food products and Temporary Permissible Levels of Radioactive Substances in Foodstuffs. Later — after 1997 — there were developed norms of permissible specific activity of cesium-137 and strontium-90 in more than 140 kinds of food products which are still in force.

Taking into account the experience of liquidation of the Chernobyl accident consequences the requirements to safety of works at NPPs were revised; criteria were developed for making decisions on measures to protect personnel and population; modern means of individual dosimetry control were introduced; special formations of permanent readiness to work in conditions of possible radiation accident were organized. At the present time within the framework of further improvement of medical and sanitary provision of the NPP personnel and population living in the observation zone we consider it a priority to carry out comprehensive monitoring of environmental and health conditions [5]. For the purpose of radiation and epidemiological investigations there was created an industrial medical and dosimetric register. Its data show that the mortality rate among the liquidators does not exceed similar indicators for the Russian Federation as a whole. The above predictions were, in particular, confirmed as a result of the analysis of data from the National Radiation Epidemiological Registry, as well as from foreign and domestic specialists [6].

Emergency medical response. The experience of liquidation of the Chernobyl accident consequences demonstrates that in case of a large-scale radiation accident it is necessary to immediately take practical measures to minimize radiation doses and to run protective measures to reduce the number of exposed persons. On the basis of the Chernobyl experience, a system of medical response to radiation accidents has been established at the Federal Medical and Biological Agency of Russia. It is a subsystem in the emergency response system of the State Corporation "Rosatom". Expert support for the FMBA emergency response system is provided by the Emergency Medical Radiation and Dosimetry Center, which is a subdivision of the Burnazyan Federal Medical and Biological Center. As well as regional emergency radiation and dosimetry centers established on the basis of the leading hygienic institutes of FMBA of Russia in the Northwestern and Ural Federal Districts (Figure 4).

The experience of iodine prophylaxis in the Chernobyl accident was used to optimize the scheme of iodine prophylaxis in accidents at nuclear installations. In this connection, a new Guidance on iodine prophylaxis in case of a radiation accident was developed (Fig. 5).

*Development of radiation medicine based on the experience of overcoming the consequences of the Chernobyl accident.* It is known that the clinic of A.I. Burnazyan Federal Medical and Biological Center has the greatest experience in diagnostics, treatment and medical rehabilitation of patients with acute radiation disease. Based on the Chernobyl experience, a classification of different forms of human radiation injuries from both external and internal radiation exposure; principles of biodosimetry and cytogenetic methods; effective treatment patterns for bone marrow form of acute radiation disease and local radiation lesions have been proposed for the first time in world practice. Currently, an innovative direction of treatment of local radiation lesions with mesenchymal stem cells in combination with microsurgical techniques is being actively developed. Encouraging experimental results have been obtained — the healing time of the wound surface is accelerated by 2 and more times. In the world such works are carried out only in a few countries, in particular, in Argentina and Japan (Fig. 6).

Analysis and comprehension of the experience of overcoming medical and sanitary consequences of the Chernobyl and other accidents, as well as further improvement of radiation safety measures are impossible without a thorough


**Рис. 4.** Система аварийного медицинского реагирования ФМБА России / **Fig. 4.** Emergency medical response system under FMBA of Russia

study of biological materials of the affected people. For this purpose our scientists were among the first in the world to propose the methodology of biobanking of cases of human radiation injuries. The study of these materials using modern high-tech techniques of molecular genetic analysis allowed to improve the detailed schemes of pathogenesis and therapy of the leading clinical syndromes of acute radiation disease and local radiation lesions [7].

*Radioprotective drugs.* After the Chernobyl accident the effectiveness of radioprotective preparations, means of prevention and treatment of acute radiation sickness was evaluated. The Federal Medical and Biological Agency of Russia has developed and introduced highly effective anti-radiation preparations, as well as individual first-aid kits for personnel and population. Based on the experience of providing specialized medical care to the victims of radiation exposure as a result of the Chernobyl accident, special portable medical radiological kits have been developed. These kits include a set of medicines and tools necessary for emergency medical care. Among them, the preparation "Lioxazole" should be mentioned. This is an alcohol solution of 2-allyloxyethanol developed by the Scientific and Production Center "Pharmzaschita" of FMBA of Russia. Lioxazole is used for the prevention and treatment of closed radiation lesions of the skin, has anti-inflammatory and stimulating regeneration. On its basis, a line of medical products

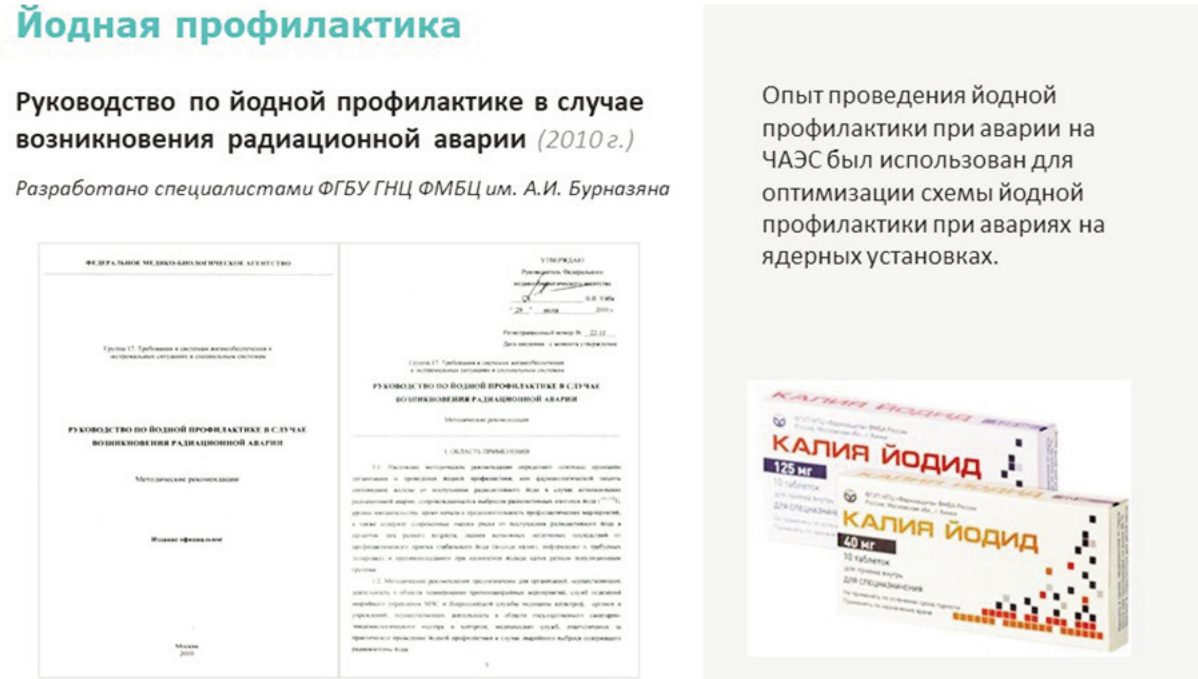


**Рис. 5.** Йодная профилактика / **Fig. 5.** Iodine thyroid blocking


**Рис. 6.** Радиационная медицина после аварии на ЧАЭС / **Fig. 6.** Radiation medicine after the Chernobyl accident

"Lioxazin" was developed for first aid and treatment of burns of varying severity (Fig. 7).

*A new coronavirus infection COVID-19 and acute radiation sickness.* The Chernobyl accident gave a powerful impetus to the search and development of new radioprotective drugs. Currently, the scale of ongoing preclinical and clinical experimental studies of radioprotectors is comparable to the scale of current research for the treatment of the new coronavirus infection. It is no coincidence that many draw an analogy between COVID-19 and radiation. Both are invisible enemies, both pose a serious danger to human life and health. It should be noted that our doctors were at the origins of the study of the pathogenesis of acute respiratory distress syndrome — the main cause of death in COVID-19 patients. They were the first in the world to conduct detailed clinical and pathological anatomical studies of acute respiratory distress syndrome in radiation sickness. The frequency of its development in severe and extremely severe Chernobyl patients was 75%. In 30% of cases of acute respiratory distress syndrome was a direct cause of death. Based on the analysis of the materials obtained as well as on the results of subsequent experimental studies, we have shown that angiotensin-converting enzyme plays a decisive role in the pathogenesis of this syndrome. Currently angiotensin-converting enzyme inhibitors are being studied as one of the most promising means of increasing radiotolerance and early pathogenetic therapy of acute radiation disease[8] — Fig. 8.

*Priority directions of radiation safety system development in Russia.* The experience of evaluation of the liquidation of medical and sanitary consequences of the Chernobyl events has created a science-based basis for radiation safety with practical implementation of the main provisions in the current regulatory and methodological documents. At the same time, there are quite good reasons for further improvement of the construction of the radiation safety system and its regulation in the Russian Federation. We associate a number of new priority projects with this, among which are the issues of harmonization of the Russian regulatory and methodological base of radiation safety with modern international documents.

The most important scientific prospect in the field of radiation safety is the radiation-hygienic study of new types of fuel. These include mixed nitride-uranium-plutonium fuel. Studies of this problem are being conducted in the course of scientific and hygienic support of the "Breakthrough" project. At the same time, doses to the personnel of the pilot demonstration power complex facilities of the Siberian Chemical Combine are evaluated. Work is underway to assess the state of health of the personnel and to develop recommendations for medical examinations of the workers of the mixed nitride-uranium-plutonium fuel production (Fig. 9).

One of the most urgent and high-priority issues of radiation safety is countering nuclear and radiation terrorism. Since 2015 FMBA of Russia has participated in the Global Initiative to Combat Nuclear Terrorism. At the expert level, close cooperation has been established with 88 partner states and six official observers of the Global Initiative to Combat Nuclear Terrorism. Our experts have made a significant contribution to the development of practical guides, manuals and working documents of the Initiative. Summarizing the 35-year experience of overcoming the consequences of the Chernobyl accident, we were the first in the world to develop a unique methodology of medical and biological research. It laid the foundation for a new scientific direction — medical nuclear forensics. The developments carried out by us were highly appreciated by the international community and recognized as the most important tool in the sphere of counteraction against global threats of nuclear-terrorist nature (Fig. 10).

According to the Fundamentals of State Policy in the Field of Nuclear and Radiation Safety of the Russian Federation for the Period until 2025*, one of the urgent tasks in the field of strengthening protection of nuclear and radiation

* Decree No. Pr-539 of the President of the Russian Federation of March 1, 2012

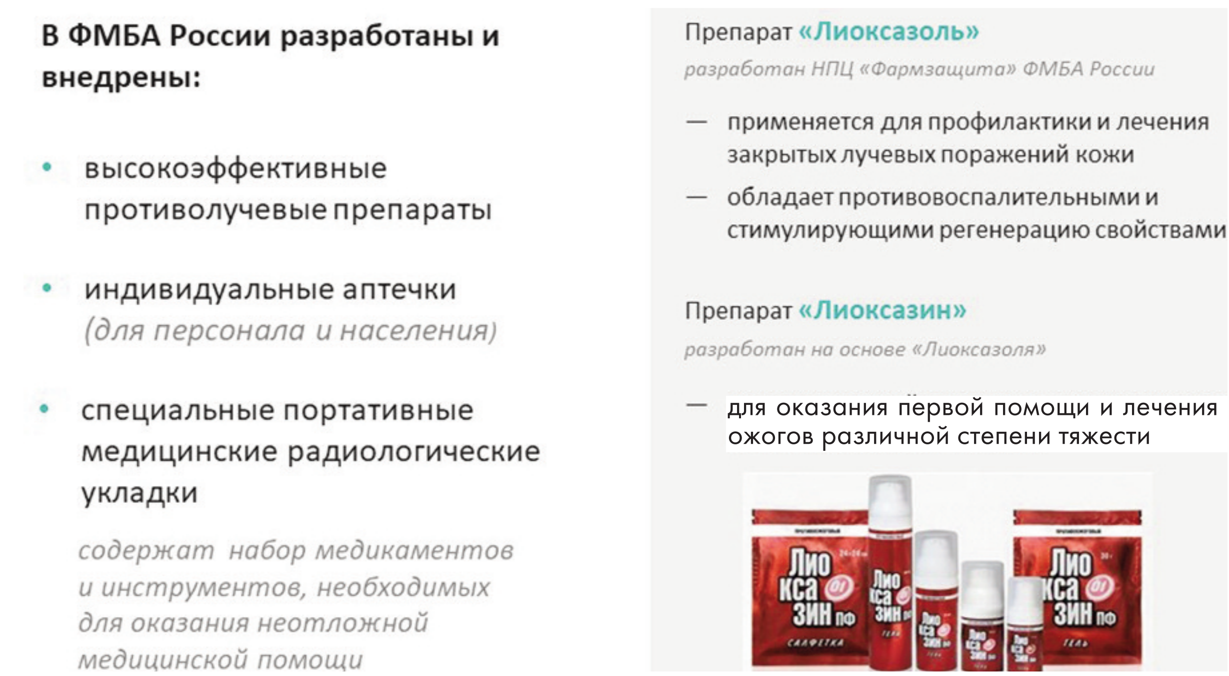


**Рис. 7.** Радиозащитные препараты / **Fig. 7.** Radioprotective drugs

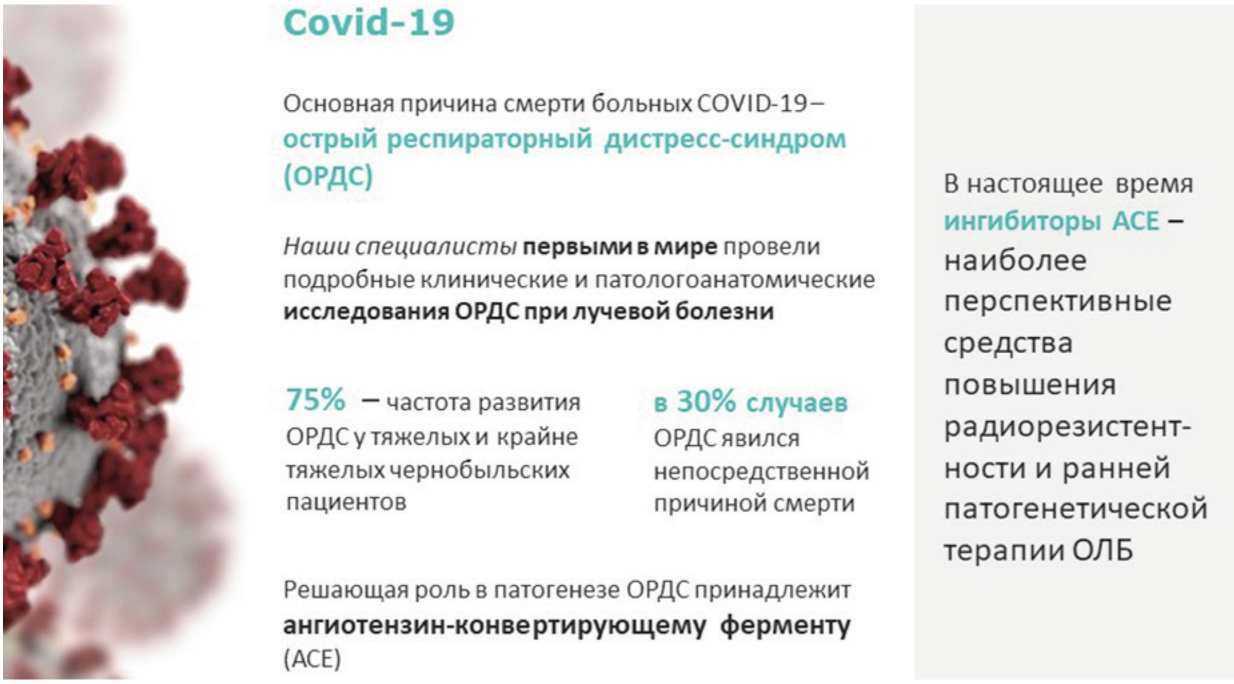


**Рис. 8.** Новая коронавирусная инфекция COVID-19 и острая лучевая болезнь / **Fig. 8.** COVID-19 and acute radiation syndrome


**Рис. 9.** Радиационно-гигиеническое сопровождение проекта «Прорыв» / **Fig. 9.** Radiation and health physics support of the "Breakthrough" project

hazardous facilities, personnel, population and the environment is modernization and development of technical, information and analytical systems of control and supervision of nuclear and radiation safety based on scientific approaches using modern technologies.

We associate the improvement and development of new medical and sanitary technologies aimed at ensuring radiation safety, including at nuclear heritage sites and territories, with the development and implementation of digital technologies, among them:

— collection of radiation-hygienic data through the formation of digital representations of the real world as a result of digitization;

— integration — processing, merging and analysis — of data using algorithms. For example, with the help of information-analytical systems using technologies for visualizing the routes of personnel and/or population movement and visualizing the radiation situation.

The created software products serve as a working tool for making management decisions to prevent possible threats related to overexposure of personnel or population. The direction of translational radiation hygiene was formed to optimize, reduce and — ideally — eliminate the existing gap between scientific research and the practice of state sanitary and epidemiological supervision over radiation safety in the handling of nuclear legacy — Fig. 11 - [9].


**Рис. 10.** Сотрудничество в рамках Глобальной инициативы по борьбе с актами ядерного терроризма
**Fig. 10.** Cooperation in the framework of the Global Initiative to Combat Acts of Nuclear Terrorism

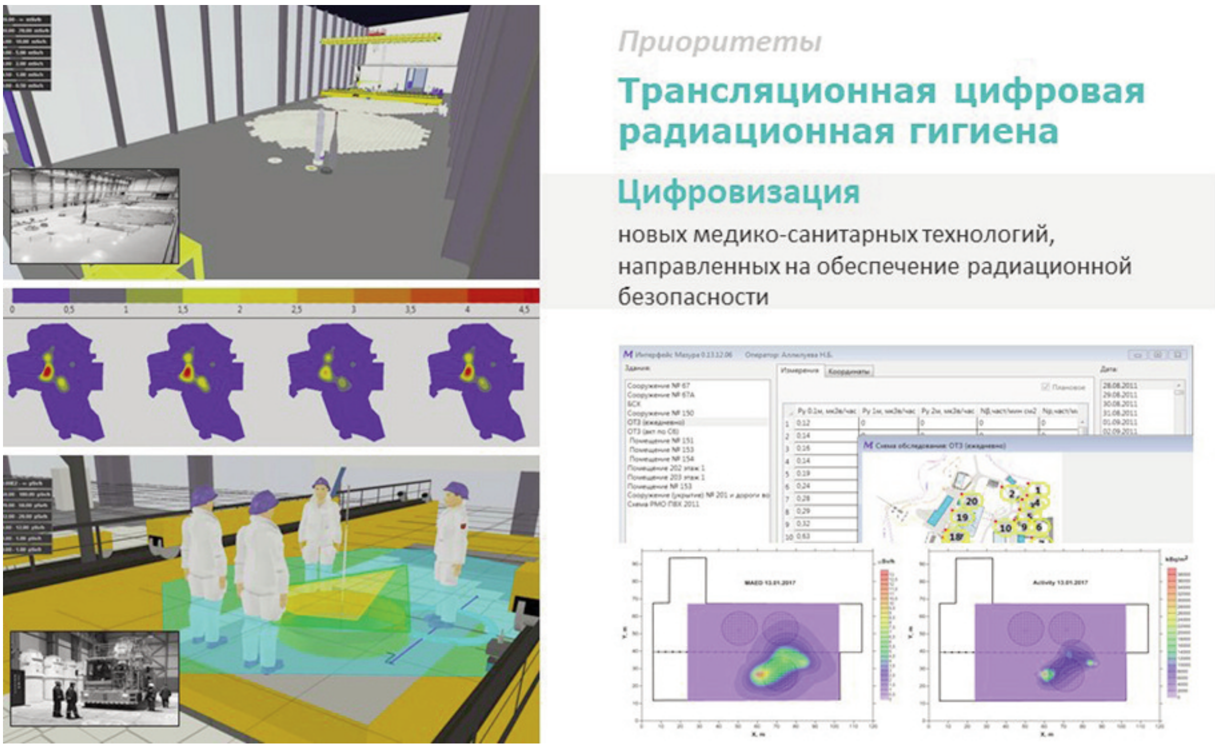


**Рис. 11.** Новые медико-санитарные технологии по обеспечению радиационной безопасности
**Fig. 11.** New medical technologies to assure radiation safety

## Conclusion

Based on the experience of overcoming the consequences of the Chernobyl accident, within the framework of further improvement of radiation safety of the personnel and population, we consider the following scientific and practical directions of further activities to be a priority:

— improvement and development of new medical and sanitary technologies aimed at ensuring radiation safety;

— completion of a unified system of radiation and hygienic response and medical aspects of human protection in the event of radiation accidents;

— further search for and development of methods and means of prevention and treatment of human radiation pathology, including innovative biomedical technologies;

— mproving the methodology for studying the distant effects of radiation exposure on the personnel of radiation hazardous facilities and the population;

— international cooperation on issues of radiation safety regulation, nuclear detection, and the development of a new scientific field — medical nuclear forensics

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*Original article*



# MEDICAL EXAMINATIONS AND PSYCHOPHYSIOLOGICAL TESTS OF NUCLEAR INDUSTRY PERSONNEL AS A TOOL FOR PREVENTION OF RADIATION ACCIDENTS

A.Yu.Bushmanov[1], A.S.Kretov[1], M.Yu.Kalinina[1], I.V.Vlasova[1], A.A.Lomteva[1], A.A.Gugina[1], A.N.Tsarev[1], E.A.Denisova[1], M.A.Soloreva[1], A.S.Samoylov[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** It is noted that at present the connection between the level of health of the worker and his professional reliability is obvious and does not require additional proof. To prevent radiation accidents caused by the human factor, medical examinations and psychophysiological tests of the personnel of enterprises operating nuclear facilities are carried out.

Legislative and normative legal acts regulating the procedure and rules for these medical examinations and inspections are reviewed.

The authors present an algorithm for making decisions on the necessity of organizing various types of mandatory medical examinations and psychophysiological examinations of employees of organizations operating nuclear facilities. The experience of specialists of the Federal Medical Biophysical Center named after A.I. Burnazyan of Federal Medical and Biological Agency of Russia shows that up to 25% of the total number of employees who underwent psychophysiological examination have inadmissible deviations (psychophysiological contraindications). This is an indication for rehabilitation measures. After completion of the rehabilitation course repeated examinations are carried out, according to the results of which 92.3% of workers have positive dynamics and return to professional activity.

**Key words:** *legal framework, medical examinations of workers in the nuclear industry, psychophysiological examination, regulatory documents*

**Conflict of interest.** The authors declare no conflict of interest

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УДК 614.29:331.435

***Оригинальная статья***



# МЕДИЦИНСКИЕ ОСМОТРЫ И ПСИХОФИЗИОЛОГИЧЕСКОЕ ОБСЛЕДОВАНИЕ ПЕРСОНАЛА АТОМНОЙ ПРОМЫШЛЕННОСТИ – ИНСТРУМЕНТ ПРЕДУПРЕЖДЕНИЯ РАДИАЦИОННЫХ АВАРИЙ

А.Ю.Бушманов[1], А.С.Кретов[1], М.Ю.Калинина[1], И.В.Власова[1], А.А.Ломтева[1], А.А.Гугина[1], А.Н.Царёв[1], Е.А.Денисова[1], М.А.Солорева[1], А.С.Самойлов[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** Отмечено, что в настоящее время связь между уровнем здоровья работника и его профессиональной надежностью – очевидна и не требует дополнительных доказательств. Для предупреждения радиационных аварий (РА) по вине человеческого фактора проводятся медицинские осмотры и психофизиологические обследования (ПФО) персонала предприятий, эксплуатирующих объекты использования атомной энергии.

Рассмотрены законодательные и нормативные правовые акты, регламентирующие порядок и правила проведения указанных медицинских осмотров и обследований.

Представлен разработанный авторами алгоритм принятия решений о необходимости организации различных видов обязательных медицинских осмотров и психофизиологических обследований сотрудников организаций, эксплуатирующих объекты использования атомной энергии. Опыт работы специалистов Федерального медицинского биофизического центра им. А.И.Бурназяна ФМБА России показывает, что из общего числа работников, прошедших ПФО, до 25% имеют недопустимые отклонения (психофизиологические противопоказания), что является показанием к проведению реабилитационных мероприятий. После завершения восстановительного курса проводятся повторные обследования, по результатам которых 92,3% работников имеют положительную динамику и возвращаются к профессиональной деятельности.

**Ключевые слова:** *законодательная база, медицинские осмотры, нормативные документы, персонал атомной промышленности, психофизиологическое обследование, радиационные аварии*

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***Contact information:***
***Andrey Yu. Bushmanov*** – Dr. Sc. (Med.), Prof.; Deputy Director General
**Address:** 46, Zhivopisnaya str., Moscow, 123098, Russia
**Phone:** +7(964) 725-32-04
**E-mail:** radclin@yandex.ru

***Контактная информация:***
***Бушманов Андрей Юрьевич*** – доктор медицинских наук, профессор; первый заместитель генерального директора
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, д. 46.
**Тел.:** +7(964) 725-32-04
**E-mail:** radclin@yandex.ru

At present, the connection between the level of health of an employee and his or her professional reliability is obvious. Carrying out measures at nuclear facilities aimed at reducing risks of emergency situations caused by the human factor is an important element of radiation protection system [1].

To achieve the aforementioned goal, organizations operating nuclear facilities must organize additional specialized medical examinations and mandatory psychophysiological examinations for certain categories of employees.

Article 3 of the Federal Law "On the Use of Atomic Energy" of November 21, 1995 170-FZ specifies the categories of facilities which are subject to this requirement:

1. Nuclear facilities — facilities and complexes with nuclear reactors, including nuclear power plants, ships and other vessels; spacecraft and aircraft, other transport and transportable vehicles; facilities and complexes with industrial, experimental and research nuclear reactors, critical and subcritical nuclear facilities; facilities, complexes, test sites, installations and devices with nuclear charges for peaceful purposes; other facilities, complexes and installations containing nuclear material, used for production, usage, recycling and transportation of nuclear fuel and materials.

2. Radiation sources — non-nuclear facilities, apparatus, equipment and products that contain radioactive substances or generate ionizing radiation.

3. Storage facilities for nuclear materials and radioactive substances, radioactive waste storage facilities — stationary facilities and installations which are not related to nuclear facilities or radiation sources and are designed for storage of nuclear materials and radioactive substances, storage or disposal of radioactive waste.

4. Fuel assembly of a nuclear reactor — a machine-building item containing nuclear materials and designed to produce thermal energy in a nuclear reactor by means of a controlled nuclear reaction.

5. Irradiated nuclear reactor fuel assemblies — fuel assemblies containing spent nuclear fuel irradiated in and removed from a nuclear reactor.

6. Nuclear materials — materials containing or capable of reproducing fissile nuclear substances.

7. Radioactive substances — non-nuclear materials emitting ionizing radiation.

8. Radioactive waste — materials and substances, as well as equipment, products, which are not subject to further use, including spent sources of ionizing radiation, which content of radionuclides exceeds the levels established in accordance with the criteria approved by the Government of the Russian Federation.

Thus, nuclear energy facilities include not only traditional nuclear industry facilities, but also a fairly wide range of organizations, from medical treatment organizations that use equipment with ionizing radiation sources or equipment that generates ionizing radiation, to enterprises that use radioactive sources for defectoscopy, geological exploration, security, including in transportation, etc.

Certain categories of workers in the field of atomic energy use as defined by the Decree of the Government of the Russian Federation "On Approval of the List of Positions of Workers of Atomic Energy Use Facilities that Must Obtain Permits of the Federal Environmental, Industrial and Nuclear Supervision Service for Works in the Field of Atomic Energy Use" No. 240 of March 3, 1997 must obtain special Rostechnadzor permits, which can be issued only if there are no medical, including psychophysiological, contraindications — Art. 27 of the Federal Law "On the Use of Atomic Energy" of 21.11.1995 170-FZ.

The fact of absence of the above contraindications is established by the results of a specialized medical examination and psychophysiological examination of employees in the field of the use of atomic energy.

In accordance with the Order of the Ministry of Health of the Russian Federation No. 749n dated July 28, 2020 from January 1, 2021 the new requirements for specialized medical examinations and psychophysiological examinations of atomic energy use facilities, the list of medical contraindications for issuing the permit for certain activities in the field of atomic energy use and the list of positions of the atomic energy use facilities employees to which such contraindications apply, as well as the form of a medical report on the presence (absence) of medical contraindications for issuing a permit to perform certain types of activities in the field of the use of atomic energy.

This specialized medical examination is independent and complementary to other types of mandatory medical examinations of workers, including medical examinations in accordance with the order of the Ministry of Health of Russia from January 28, 2021 № 29n.

Employees of organizations on the list of operating especially radiation hazardous and nuclear-hazardous productions and facilities in the field of atomic energy use undergo medical examinations and mandatory psychophysiological examinations in medical treatment organizations subordinated to the authorized federal executive authority. Currently, this is the Federal Medical and Biological Agency of Russia — Federal Law No. 35-FZ dated March 8, 2011 "The Statute on Discipline of the Employees of the Organizations Operating Radiation-Industry and Nuclear Especially Hazardous Facilities and Facilities of Atomic Energy Use"; the Russian Government Executive Order No. 597 dated July 20, 2011 "On the List of Operating Organizations Subject to the Federal Law "The Statute on Discipline of Employees of Organizations Operating Radiation-Industry and Nuclear Especially Hazardous Facilities and Objects."

Specialized medical examinations and psychophysiological examinations of workers in the field of the use of atomic energy are carried out at occupational pathology centers. They are conducted when it is difficult to determine an employee's professional suitability due to a disease or when the employee does not agree with the results of the examinations.

When organizing mandatory medical examinations of employees in the field of the use of atomic energy it is necessary to take into account the mandatory medical examinations and psychiatric examinations of employees involved in certain types of work and in work with harmful and hazardous working conditions — Article 213 of the Labor Code of the Russian Federation.

Employees of the field of use of atomic energy are required to undergo psychiatric examination in cases of contact with an industrial factor or type of work, which are provided by the List approved by the Government of the Russian Federation on April 28, 1993 № 377; the Rules for mandatory psychiatric examinations established by the Government of the Russian Federation on September 23, 2002 № 695 and the order of the FMBA of Russia on June 9, 2018 № 121.

Employees of the field of atomic energy use shall undergo additional preliminary (periodic) medical examinations in cases of contact with an industrial factor (working conditions

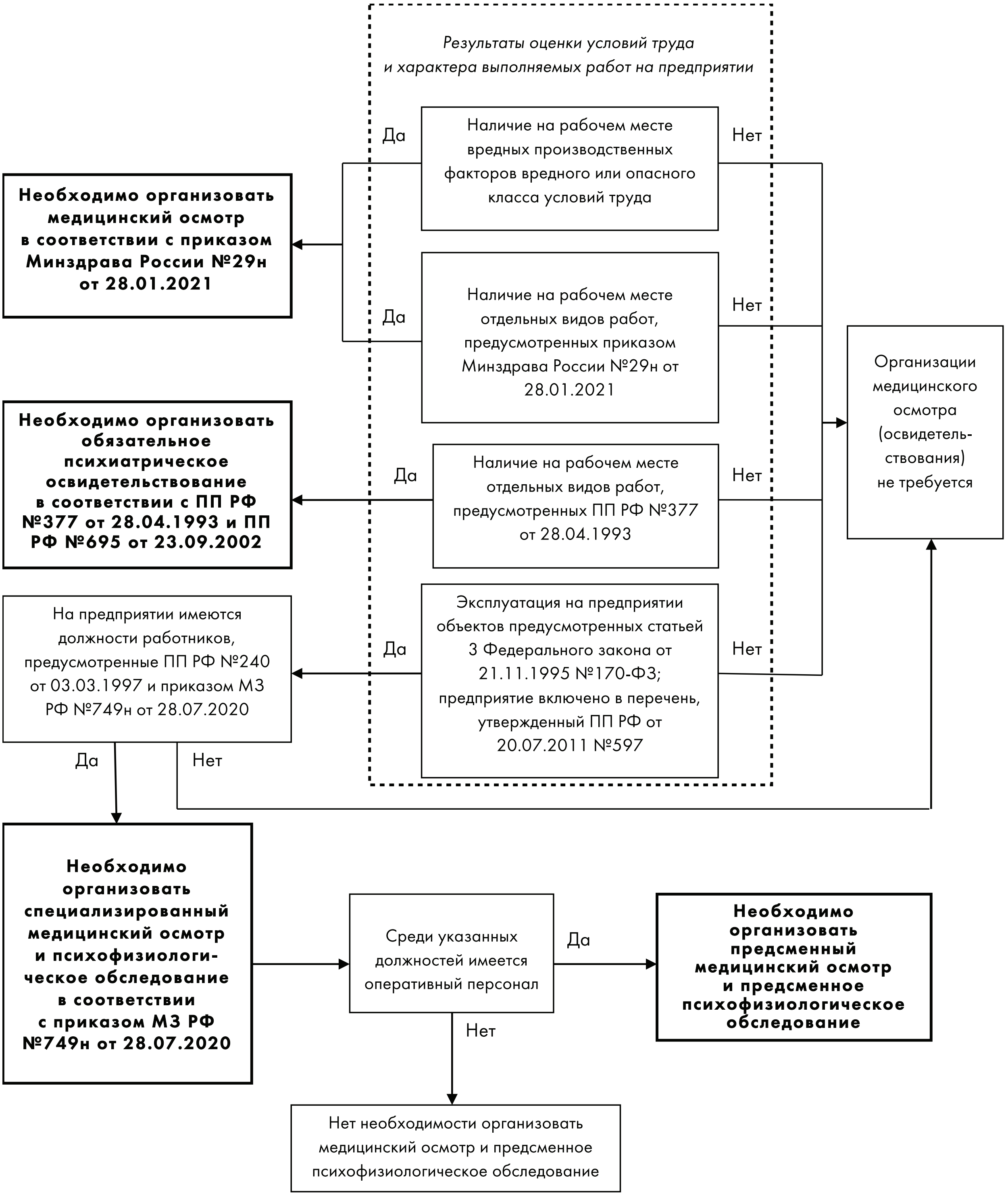


**Рисунок.** Алгоритм принятия решений о необходимости организации различных видов обязательных медицинских осмотров и психофизиологических обследований на предприятиях, эксплуатирующих объекты использования атомной энергии

**Figure.** Algorithm of decision-making on the necessity of organizing various types of mandatory medical examinations and psychophysiological examinations at enterprises operating nuclear energy facilities

class 3.1 or higher) or type of work stipulated by Order No. 29n of the Ministry of Health of Russia dated January 28, 2021.

It should be noted that according to the Order of the Ministry of Health of Russia № 29n dated January 28, 2021 all workers undergoing a periodic medical examination in respect of a harmful production factor "ionizing radiation" from April 1, 2021 are subject to compulsory psychophysiological examination.

The algorithm for making decisions on the necessity of organizing various types of mandatory medical examinations and psychophysiological examinations at enterprises operating nuclear facilities is shown in the figure.

Thus, when organizing medical examinations of employees in the field of the use of atomic energy it is necessary to take into account the following:

1. In order to be admitted to work in the field of the use of atomic energy, certain categories of employees must undergo a specialized medical examination and psychophysiological examination regardless of the results of the special assessment of working conditions in order to prevent emergency situations caused by the human factor.

2. Employees of the field of use of atomic energy are additionally subject to requirements of Article 213 of the Labor Code of the Russian Federation on passing mandatory psychiatric examinations in accordance with Resolutions of the Government of the Russian Federation No. 377 of April 28, 1993 and No. 695 of September 23, 2002, on condition of:

- presence at the workplace of a production factor from the List approved by Decree No. 377 of the Government of the Russian Federation on April 28, 1993;

- availability at the workplace of the type of work envisaged by the List approved by Russian Federation Government Decree No. 377 of April 28, 1993.

3. Employees of the field of the use of atomic energy shall be additionally required to undergo mandatory preliminary (periodic) medical examinations in accordance with Order of the Russian Ministry of Health no. 29n of January 28, 2021 (until April 1, 2021 — Order of the Russian Ministry of Health and Social Development no. 302n of April 12, 2011), provided

- presence at the workplace of a production factor stipulated by Order of the Russian Ministry of Health No. 29n of January 28, 2021, characterized by a harmful or hazardous class of working conditions (3.1 or higher);

- availability at the workplace of the type of work stipulated by Order of the Ministry of Health of Russia No. 29n of January 28, 2021.

4. According to Art. 46 of the Federal Law of November 21, 2011 № 323-FZ, during medical examinations the results of previous (not later than one year ago) medical examinations, health examinations, confirmed by medical records of the patient, may be taken into account.

In conclusion it should be noted that up to 500 examinations of nuclear industry employees working under conditions of exposure to ionizing radiation from 3.25 to 1.62 mSv per year are performed at the State Research Center — A. I. Burnazyan Federal Medical Biophysical Center of the Federal Medical and Biological Agency of Russia. Professional duties of the examined employees include the need to make and implement responsible decisions.

Experience shows that out of the total number of workers who underwent psychophysiological examination, 25.1% have unacceptable deviations (psychophysiological contraindications), which is an indication for rehabilitation measures. After completion of the rehabilitation course repeated examinations are carried out, according to the results of which 92.3% of workers have positive dynamics and return to professional activity.

Mandatory medical examinations and psychophysiological examination of nuclear industry personnel are effective elements of the radiation protection system. They make it possible to influence the risks of radiation accidents caused by the human factor and to take timely targeted rehabilitation measures.

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# ASSESSMENT OF THE RADIATION AND HEALTH PHYSICS SITUATION IN THE AREA OF SHIP REPAIR ENTERPRISES IN KAMCHATKA KRAI

D.V.Isaev[1], N.K.Shandala[1], V.G.Starinskiy[1], A.V.Titov[1], V.V.Shlygin[1], Y.S.Belskikh[1], R.A.Starinskaya[1], Y.V.Gushchina[1], K.Y.Oskina[1], A.M.Komlev[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** *The objectives of the study* are to examine the radiation and health physics situation in the area of ship repair enterprises servicing ships with nuclear power installation; to assess its possible impact on the environment and the population.
*Materials and research methods.* The study of radiation and health physics situation on the territory was conducted by walking gamma survey using portable gamma spectrometric complexes MKS-01A "Multirad-gamma" and MKS-AT6101C. Gamma-spectrometric and radiochemical methods of analysis were used to determine the specific activity of man-made and natural radionuclides in environmental samples.
*Results of the study and their analysis.* Practical medical and hygienic measures to study the radiation and health physics situation were carried out in 2019. It was found that the ambient equivalent dose rate in the areas of ship repair enterprises is at the level of regional values and does not exceed 0.12 μSv/h. Radionuclide specific activity in the soil of the surveyed areas does not exceed 4.5 Bq/kg — for $^{90}$Sr and 12 Bq/kg — for $^{137}$Cs, which does not exceed the established norms for unrestricted use of solid materials. Radionuclide content in the sea water samples taken in the area of closed administrative territorial unit Krasheninnikov Bay does not exceed on average: for $^{137}$Cs — 7 mBq/L, for $^{90}$Sr — 2.1 mBq/L. When comparing the results obtained with the official data on the radionuclide content in the water of Avacha Bay ($^{90}$Sr up to 2.08 mBq/L at the annual average of 1.14 mBq/L), we may state that they are at the same level as the regional ones. Radionuclide content in bottom sediment samples varies within the following limits: for $^{137}$Cs — from 0.14 to 3 Bq/kg, for $^{90}$Sr — from 0.11 to 1.5 Bq/kg and is similar to the general values for soil samples.
Thus, the radiation and health physics characteristics of the study area vary little and remain practically at the level of the results of studies conducted in 2014-2015. The content of man-made radionuclides in the samples of environmental objects is at the level of average values typical for the region.
Potentially radiation-hazardous works carried out in 2019 at enterprises of closed administrative territorial unit Vilyuchinsk had no reliable radiation impact on the environment and population.
**Key words:** *cesium-137, closed administrative territorial unit Vilyuchinsk, dose rate, Kamchatka Krai, nuclear submarines, radiation and hygienic situation, radiation safety, radiochemistry, recycling, ship repair enterprises, spectrometry, strontium-90*

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# ОЦЕНКА РАДИАЦИОННО-ГИГИЕНИЧЕСКОЙ ОБСТАНОВКИ В РАЙОНЕ РАСПОЛОЖЕНИЯ СУДОРЕМОНТНЫХ ПРЕДПРИЯТИЙ В КАМЧАТСКОМ КРАЕ

Д.В.Исаев[1], Н.К.Шандала[1], В.Г.Старинский[1], А.В.Титов[1], В.В.Шлыгин[1], Ю.С.Бельских[1], Р.А.Старинская[1], Ю.В.Гущина[1], К.Ю.Оськина[1], А.М.Комлев[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** *Цели исследования* – изучить радиационно-гигиеническую обстановку в районе расположения судоремонтных предприятий, обслуживающих корабли с ядерными энергетическими установками (ЯЭУ); оценить её возможное воздействие на окружающую среду и население.
*Материалы и методы исследования.* Исследование радиационно-гигиенической обстановки непосредственно на территории проводилось методом пешеходной гамма-съемки мощности амбиентного эквивалента дозы гамма-излучения (МАЭД ГИ) с использованием портативных гамма-спектрометрических комплексов МКС-01А «Мультирад-гамма» и МКС-АТ6101С. Для определения удельной активности техногенных и естественных радионуклидов в пробах объектов окружающей среды применялись гамма-спектрометрические и радиохимические методы анализа.
*Результаты исследования и их анализ.* Практические медико-гигиенические мероприятия по исследованию радиационной гигиенической обстановки проводились в 2019 г. Было установлено, что МАЭД ГИ в районах

расположения судоремонтных предприятий находится на уровне региональных значений и не превышает 0,12 мкЗв/ч. Удельная активность радионуклидов в почве обследуемых территорий не превышала 4,5 Бк/кг – по $^{90}Sr$ и 12 Бк/кг – по $^{137}Cs$, что не выше установленных нормативов для неограниченного использования твердых материалов. Содержание радионуклидов в пробах морской воды, отобранной в районе закрытого административно-территориального образования – ЗАТО (бухта Крашенинникова), не превышало в среднем: по $^{137}Cs$ – 7 мБк/л; по $^{90}Sr$ – 2,1 мБк/л. При сравнении полученных результатов с официальными данными о содержании радионуклидов в воде Авачинской бухты ($^{90}Sr$ – до 2,08 мБк/л при среднегодовом – 1,14 мБк/л) можно было констатировать, что они находились на одном уровне с региональными. Содержание радионуклидов в пробах донных отложений варьировалось в следующих пределах: по $^{137}Cs$ – от 0,14 до 3 Бк/кг; по $^{90}Sr$ – от 0,11 до 1,5 Бк/кг и было сходно с общими значениями для проб почвы.
Таким образом, радиационно-гигиенические характеристики исследуемого района слабо варьировались и оставались практически на уровне результатов исследований, проведенных в 2014–2015 гг. Содержание техногенных радионуклидов в пробах объектов окружающей среды находилось на уровне средних значений, характерных для региона. Потенциально радиационно опасные работы, проводившиеся в 2019 г. на предприятиях ЗАТО г. Вилючинск, не оказали достоверного радиационного влияния на окружающую среду и население.

**Ключевые слова:** *атомные подводные лодки, закрытое административно-территориальное образование г.Вилючинск, Камчатский край, мощность дозы, радиационная безопасность, радиационно-гигиеническая обстановка, радиохимия, спектрометрия, стронций-90, судоремонтные предприятия, утилизация, цезий-137*

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***Contact information:***
***Vitaliy .G. Starinskiy*** – Researcher
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (499) 190-96-91
**E-mail:** vitalstar90@mail.ru

***Контактная информация:***
***Старинский Виталий Григорьевич*** – научный сотрудник
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, д. 46
**Тел.:** +7 (499) 190-96-91
**E-mail:** vitalstar90@mail.ru

## Introduction

At present the Federal Target Program "Industrial Utilization of Weapons and Military Equipment of the Nuclear Complex in 2011-2015 and until 2020" realisation is coming to an end in Russia. One of its tasks is to ensure public health and environmental safety during the disposal of weapons and military equipment[1]. A study of the radiation and hygienic situation in the area of ship repair facilities that dismantled decommissioned submarines with nuclear power units and former onshore technical bases that stored and processed spent nuclear fuel was conducted.

The study area is an area of closed administrative-territorial formation Vilyuchinsk. Two enterprises are located on its territory: Joint Stock Company "North-Eastern Repair Center" and the Center for Radioactive Waste Management — Vilyuchinsk Branch of the Far East Center for Radioactive Waste Management — a branch of Federal State Unitary Enterprise "Federal Environmental Operator".

The Northeast Repair Center is located in Seldevaya Bay. The center repairs nuclear and diesel submarines, surface ships, auxiliary vessels, and dismantles nuclear submarines[2]. Nearby is one of the districts of the closed administrative territorial entity of Vilyuchinsk — the settlement of Seldevaya. As part of the state contract with the Federal State Unitary Enterprise Enterprise for Radioactive Waste Management, work was performed at the end of 2019 to lift and subsequently transport the afloat reactor units to a disposal site in Primorsky Krai[3].

Vilyuchinsk Branch of DalRAO Far East Center — Branch of Federal State Unitary Enterprise "Federal Environmental Operator" was established on the territory and on the basis of the property of the Pacific Fleet coastal technical bases in Krasheninnikov Bay.

The coastal technical base provided:

- Recharging of nuclear submarine reactors using floating technical bases at nuclear submarine repair sites;
- Recharging of activity filters of the 1st and 3rd circuits of nuclear power plants of nuclear submarines;
- Reception and storage of solid radioactive waste in onshore storage facilities;
- Short-term mooring at the floating berth of nuclear service ships (Project 326M floating maintenance base) and technical liquid tankers (Project 1783 and 1783A) and temporary storage of spent fuel assemblies, liquid radioactive waste, substandard fuel assemblies in them;
- Storage and transfer of special technological (reloading) equipment to the floating technical base[4].

At present, the enterprise is solving tasks related to temporary storage of radioactive waste. Since 2016, work has been underway at the Vilyuchinsk branch to remove waste from storage facilities, to place it in shipping containers that will be transported by sea to the Regional Center for Conditioning and Long-Term Storage of the DalRAO Far East Center for subsequent immobilization and placement in long-term storage. After complete withdrawal of radioactive waste, the facilities will be decontaminated, and the area will be "rehabilitated". At present, all solid radioactive waste has been completely removed from the Vilyuchinsk Branch to the pier of the Severo-Vostochny Repair Center.

Vilyuchinsk, located on the coast of Tarja Bay (Krasheninnikov Bay) of Avacha Bay, 25 km from the regional center, was created in accordance with the Decree of the Presidium of the RSFSR Supreme Soviet of October 16, 1968 by

[1] 1 URL: http://stat.mil.ru/pubart.htm?id=11845577@cmsArticle (10/19-2020)
[2] URL: https://сврц.рф/ (10/1920)
[3] URL: http://nuclear-submarine-decommissioning.ru/node/1246 (10/1920)

[4] Progress Research Report / State Research Center — Burnazyan Medical Biophysical Center of FMBA of Russia. Moscow, 2014.


**Рис. 1.** Схема расположения исследуемых территорий в ЗАТО Вилючинск Камчатского края[6]
**Fig. 1.** Scheme of the location of the study areas in the closed administrative territorial unit Vilyuchinsk, Kamchatka Krai[6]

merging the settlements Primorsky, Sovetskiy, Seldevaya, Rybachiy, Yagodny, Lakhtazhny and Bogatyrevka[5]. The location of the studied territories is shown in Fig. 1.

**The objectives of the study** are to examine the radiation and health physics situation in the area of ship repair facilities servicing ships with nuclear power installations; to assess its possible impact on the environment and the population.

**Materials and methods of research.**

The following parameters were measured within the research:

- gamma equivalent dose rate of ambient gamma radiation;
- specific activity of man-made radionuclides in soil;
- specific activity of man-made radionuclides in marine bottom sediments and seawater.

Environmental sampling was conducted in accordance with regulatory documents and methodological guidelines[7-10].

Soil sampling points were located evenly over the area of the study in areas with undisturbed soil cover. Samples of 1 kg were taken from the surface layer of five centimeters.

An average seawater sample was taken by excavating equal volume (5.0 l) water samples at a distance of 1-2 m from the shore for a set time (10-20 min) up to the required total volume (20 l) of the sample. Seawater sampling points were selected in the coastal water areas free from aquatic vegetation and other objects.

The activity of gamma-emitting radionuclides in the selected samples was measured by gamma-spectrometric method on a CANBERRA gamma-spectrometer with a germanium detection unit in accordance with the measurement procedure [1].

Determination of 90Sr specific activity in selected samples was performed on radiometric units UMF-2000 after radiochemical separation of radionuclides in accordance with the methodical instructions [2].

The ambient equivalent dose rate of gamma-radiation on the territory was studied in accordance with the methodological recommendations by the method of continuous walking gamma survey [3]. Portable spectrometric units MKS-01A "Multirad-M" and MKS-AT6101C were used for measurements of ambient equivalent dose rate of gamma radiation throughout the territory. Range of recorded gamma radiation energy MKS-01A "Multrad-M" with a detector unit BDKS-63-01A ranges from 0.04 to 3 MeV; measurement range of photon radiation dose equivalent ambient dose rate is from 0.03 to 60 μSv/h. Maximum permissible basic relative error of gamma radiation dose rate ambient equivalent measurements ranges from 0.03 to 0.05 μSv/h and is 25%; in the range from 0.5 to 60 μSv/h — (25% — 0.167 MAED). The range of registered energy of gamma radiation of spectrometer MKS-AT6101S with detector unit BDKG-11M is 0.02 to 3 MeV, the measurement range of photon radiation ambient dose equivalent power is 0.03 to 150 μSv/h. Maximum permissible basic relative error of measurements in the range from 0.01 to 150 μSv/h is 20%. These devices allow to conduct gamma survey of the area with the possibility of radionuclide identification and referencing to geographical coordinates using global navigation system (GPS). The appearance of the devices in use is shown in Fig. 2.

**Results of the study and their analysis.**

Comparison of the measurement results of the ambient equivalent dose rate of gamma radiation in 2019 with the results of earlier measurements are shown in Table 1.

The values of ambient equivalent dose rate of gamma radiation obtained in 2019 were at the same level throughout the territory and within the variation of natural radiation background for Kamchatka Krai (0.10-0.12 Sv/h), and at the same level as the results of previous studies conducted in 2014-2015. [6]. The scheme of the course of the survey of the ambient equivalent dose rate of gamma-radiation in 2019 is shown in Fig. 3.

In the course of works on the territory of closed administrative territorial unit of Vilyuchinsk we took and analyzed samples of environmental objects on the content of man-made and natural radionuclides. Table 2 shows the results of the analysis of soil samples for radionuclide content in the studied area.

Levels of $^{137}$Cs and $^{90}$Sr technogenic radionuclides content in soil in the territory of Vilyuchinsk Closed Administrative Territorial Unit are generally uniform. The maximum values of $^{90}$Sr and $^{137}$Cs content in the soil of the area of the location of JSC "Northeastern Repair Center" and Primorsky area are 4.5 and 12 Bq/kg respectively, which does not exceed the established norms for unrestricted use of solid materials[11].

[5] URL: http://www.viluchinsk-city.ru/city/history.php (09.10.2019)
[6] URL: http://www.google.ru/maps (10/26/2020).
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**Рис. 2.** Спектрометрические комплексы МКС-01А «Мультирад-М» и МКС-АТ6101С [4, 5]
**Fig. 2.** Spectrometric complexes MKS-01A "Multirad-M" and MKS-AT6101S [4, 5]

*Таблица 1 / Table No.1*

**Распределение значений МАЭД ГИ на территории ЗАТО г. Вилючинск в 2019 г.**
Distribution of the ambient equivalent dose rate of gamma radiation values in the territory of the closed administrative territorial unit Vilyuchinsk in 2019

| Место измерения Place of measurement | Количество измерений, абс, Number of measure-ments, abs. | Значения МАЭД ГИ, мкЗв/ч* Ambient equivalent dose rate of gamma radiation values, µSv/h* | |
|---|---|---|---|
| | | max | медиана median |
| Р-н Приморский Primorskiy district | 2327 | 0,12 | 0,08 (0,05–0,10) |
| Пос. Сельдевая Seldevaya village | 558 | 0,11 | 0,07 (0,05–0,09) |
| Р-н АО СВРЦ JSC Northeast Repair Center Disctrict | 194 | 0,12 | 0,07 (0,05–0,10) |
| Дорога отделение Вилючинск – АО СВРЦ Vilyuchinsk Branch –JSC Northeast Repair Center Road | 1245 | 0,09 | 0,04 (0,03–0,05) |
| Р-н отделения Вилючинск Vilyuchinsk Branch Disctrict | 272 | 0,09 | 0,04 (0,03–0,05) |
| Дорога отделение Вилючинск – р-н Рыбачий Vilyuchinsk Branch –Rybachiy District Road | 698 | 0,09 | 0,04 (0,03–0,06) |
| Р-н Рыбачий Rybachiy District | 3723 | 0,12 | 0,05 (0,03–0,06) |
| Прочие территории Other territories | 923 | 0,11 | 0,04 (0,03–0,06) |
| По результатам работ в 2014–2015 гг.[4] According to the results of work in 2014-2015[4] | | 0,10 | 0,08 |
| Общие значения для Камчатского края [6]/ Total values for Kamchatka Krai [6] | | 0,13 | 0,09 |

Примечание: * максимальные значения, а также границы средних (указаны в скобках) приведены с запасом на расширенную неопределённость измерений
Note. * maximum values, as well as the boundaries of the averages (in parentheses) are given with a reserve for the expanded uncertainty of measurements

The data in Table 2 show that activity values of natural radionuclides in soil in the territories of closed administrative territorial unit Vilyuchinsk obtained in 2019 were almost at the same level as average activity values in the territory of Vilyuchinsk Far East Center "DalRAO" in 2014-2015.

Radionuclide content in the seawater samples (3 samples) taken in the area of Vilyuchinsk Branch of DalRAO Far East Center did not exceed on average: for $^{137}Cs$ — 7 mBq/L; for $^{90}Sr$ — 2.1 mBq/L. When comparing the obtained results with reference data on radionuclide content in the water of Avacha Bay ($^{90}Sr$ — up to 2.08 mBq/L with annual average value of 1.14 mBq/L), one could state that they were at the same level as the regional ones [6].

Radionuclide content in bottom sediment samples (3 samples) varies within the following limits: for $^{137}Cs$ — from 0.14 to 3 Bq/kg; for $^{90}Sr$ — from 0.11 to 1.5 Bq/kg.

According to the Federal State Budgetary Institution "Typhoon", in 2019 in the observation points of the 100-km zone of radiation hazardous objects in Kamchatka Region, the average monthly values of atmospheric deposition varied from 0.3 to 0.85 Bq/m$^2$×day. They averaged 0.5 Bq/m$^2$×day and did not exceed 183 Bq/m$^2$ year in total for the year [6]. These values do not differ from the average values typical for the whole Kamchatka Krai in 2019.

**Conclusion**

A study of the radiation situation in the area of the closed administrative territorial unit Vilyuchinsk in 2019 showed:

1. In all investigated areas of closed administrative territorial unit Vilyuchinsk the values of ambient equivalent dose rate of gamma-radiation are at the level of regional values and correspond to the average values of ambient equivalent dose rate of gamma-radiation obtained in the course of previous studies (2014-2016). It can be confidently stated that during all the years of research the gamma-radiation ambient dose equivalent rate in the area of closed administrative territorial unit Vilyuchinsk has not changed.

2. Obtained in 2019 values of man-made and natural radionuclides in soil, bottom sediments and sea water — both in the area where the enterprises are located and in nearby settlements (Primorsky, Rybachy and Seldevaya districts) — are at the same level as the average values across the region and correspond to the values obtained in the course of studies conducted in 2014-2015.

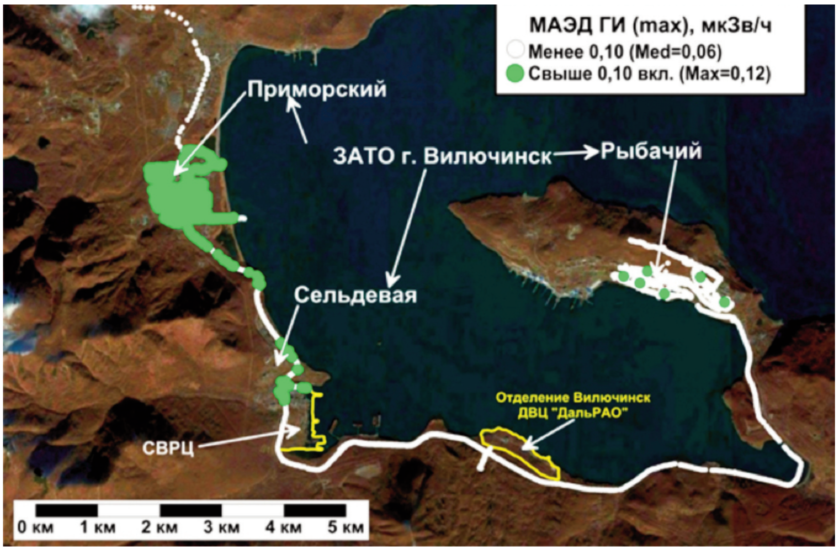


**Рис. 3.** Схема хода съемки МАЭД на территориях ЗАТО г.Вилючинск в 2019 г.[6]
**Fig. 3.** Diagram of the survey progress of the ambient equivalent dose rate of gamma radiation in the territories of the closed administrative territorial unit Vilyuchinsk in 2019 [6]

*Таблица 2/ Table No. 2*

**Статистические характеристики распределения величин удельной активности радионуклидов в почве, полученных в ходе работ в 2019 г., в сравнении с результатами исследований, проводившихся в 2014-2015 гг.[4]**
Statistical characteristics of the distributions of specific activity values of radionuclides in soil obtained during the work in 2019, compared with the results of studies conducted in 2014-2015 [4]

| Территория Territory | Год Year | Кол-во изм., абс. Number of measurements, | Диапазон значений удельной активности, Бк/кг* / Specific activity value range, Bq/kg* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $^{90}$Sr | $^{137}$Cs | $^{232}$Th | $^{226}$Ra | $^{40}$K | $^{235}$U |
| Р-н отделения Вилючинск – ДВЦ «ДальРАО» Vilyuchinsk Far Eastern Center "DalRAO" district | 2019 | 6 | <0,2-1,3 | 0,17-5 | 1–14 | 3,1–8,0 | 70–230 | – |
| | 2014–2015 – пром. площадка Industrial territory in | – | 1,5** (<0,2–7,0) | 9,2** (0,13–116.0) | – | – | – | – |
| Р-н Приморский Primorskiy District | 2019 | 8 | <0,2–1,3 | 0,18–12,0 | 2,8–6,8 | 4,1–9,2 | 180–290 | 0,67–2,0 |
| Р-н Рыбачий Rybachiy District | 2019 | 16 | <0,2–1,1 | 0,16–5,4 | 3,2–7,5 | 5,3–13,0 | 147–240 | 0,64–3,0 |
| Пос. Сельдевая АО СВРЦ Seldevaya Village — JSC Northeast Repair Center | 2019 | 5 | <0,2–4,5 | <0,44–0,8 | 4,4–10,0 | 3,8–7,5 | 145–250 | 0,61–2,0 |
| Проч. территории /Other terr. | 2019 | 7 | <0,2–0,77 | 0,33–8,3 | 3,8–8,6 | 3–5 | 43–300 | 0,5–1,3 |

Примечание: * значения вычислены с учётом расширенной неопределённости измерений, ** приведены средние значения
**Note**: * values are calculated taking into account the expanded uncertainty of measurements, ** average values are given

3. The content of man-made and natural radionuclides in samples of bottom sediments generally corresponds to the content of radionuclides in soil samples of the region.

4. According to the Federal State Budgetary Institution "Typhoon", monthly average atmospheric precipitation in 2019 did not differ from the average values typical for the whole Kamchatka Territory.

In conclusion, we can state that the radiation and hygienic situation in the area of Vilyuchinsk Closed Administrative Territorial Unit is generally satisfactory. The operation of ship repair facilities and enterprises servicing ships with nuclear power installations had no significant radiation impact on the environment and the population.

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*Original article*


# PECULIARITIES OF USING LYMPHOCYTE TEST TO PREDICT THE SEVERITY OF ACUTE RADIATION INJURY

A.O.Lebedev[1], A.S.Samoylov[1], V.Yu.Solovyev[1], N.N.Baranova[1,2], E.A.Gudkov[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation
[2] Russian Medical Academy of Continuous Professional Education, the Ministry of Health of the Russian Federation, Moscow, Russian Federation

**Abstract.** One of the methods of biological dosimetry is the use of information on the concentration of lymphocytes in the peripheral blood of victims in the first days after irradiation.
*The aim of the study* was to validate the lymphocyte test method for predicting the severity of acute radiation injury, taking into account the dose rate factor.
*Materials and research methods.* The method of investigation was a correlational analysis of clinical, dosimetric and laboratory data of the victims of the accident at the Chernobyl nuclear power plant in 1986 (n=65) and in radiation accidents with gamma-neutron irradiation (n=19). The data were taken from the database of acute radiation injuries in humans of A.I. Burnazyan Federal Medical Biophysical Center of the Federal Medical and Biological Agency of Russia.
*Results of the study and their analysis.* The results of correlation analysis indicated that average lymphocyte concentration in the range of 0.4-0.8×10$^9$/l on day 3-6 post-irradiation with dose rates greater than 2 Gy/h resulted in an average dose estimate which was 40.0% higher than that for dose rates of less than 2 Gy/h. Absolute error of dose estimation is (±1.0-1.5) Gy. For lymphocyte concentrations higher than 0.8×10$^9$/l the prognosis is uncertain: the range of dose assessment variability is 1-4 Gy. At a lymphocyte concentration of less than 0.4×10$^9$/l the average dose estimate is more than 4.0 Gy, corresponding to a severe or extremely severe degree of acute radiation disease. The predicted degree of severity of radiation injuries in the presence of the neutron component of radiation is lower in comparison with the predictions based on the data on the victims of the Chernobyl accident. It is concluded that the identified dependencies can be used for medical triage of the victims at advanced stages of medical evacuation. For the purpose of correct routing of medical evacuation to specialized centers, it is advisable to allocate 4 treatment-evacuation groups.
**Key words:** *acute radiation syndrome, disaster, dosimetry, emergency situation, lymphocyte tests, triage*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***


# ОСОБЕННОСТИ ИСПОЛЬЗОВАНИЯ ЛИМФОЦИТАРНОГО ТЕСТА ДЛЯ ПРОГНОЗИРОВАНИЯ СТЕПЕНИ ТЯЖЕСТИ ОСТРОГО ЛУЧЕВОГО ПОРАЖЕНИЯ

А.О.Лебедев[1], А.С.Самойлов[1], В.Ю.Соловьёв[1], Н.Н.Баранова[1,2], Е.А.Гудков[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия
[2] ФГБОУ ДПО «Российская медицинская академия непрерывного профессионального образования» Минздрава России, Москва, Россия

**Резюме**. Одним из методов биологической дозиметрии является использование информации о концентрации лимфоцитов в периферической крови пострадавших в первые дни после облучения.
*Цель исследования* – валидация метода лимфоцитарного теста для прогнозирования степени тяжести острого лучевого поражения с учётом фактора мощности дозы.
*Материалы и методы исследования.* Метод исследования – корреляционный анализ клинико-дозиметрических и лабораторных данных пострадавших при аварии на Чернобыльской АЭС – ЧАЭС в 1986 г. (n=65) и при радиационных авариях с гамма-нейтронным облучением (n=19). Данные взяты из базы данных по острым лучевым поражениям человека Федерального медицинского биофизического центра им. А.И.Бурназяна ФМБА России.
*Результаты исследования и их анализ.* По результатам корреляционного анализа установлено, что при средней концентрации лимфоцитов в диапазоне 0,4–0,8×10$^9$/л на 3-и – 6-е сутки после облучения при мощности дозы более 2 Гр/ч в среднем оценка дозы оказывается выше на 40,0%, чем для мощности дозы менее 2 Гр/ч. Абсолютная погрешность оценки дозы – (±1,0–1,5) Гр. При концентрации лимфоцитов более 0,8×10$^9$/л прогноз оказывается неопределенным: диапазон вариабельности оценки дозы – 1–4 Гр. При концентрации лимфоцитов менее 0,4×10$^9$/л средняя оценка дозы составляет

более 4,0 Гр, что соответствует тяжелой или крайне тяжелой степени тяжести острой лучевой болезни (ОЛБ). Прогнозируемая степень тяжести лучевого поражения при наличии нейтронной компоненты излучения оказывается ниже по сравнению с прогнозом, основанным на данных о пострадавших при аварии на ЧАЭС. Сделаны выводы: выявленные зависимости можно использовать для медицинской сортировки пострадавших на передовых этапах медицинской эвакуации; в целях корректной маршрутизации медицинской эвакуации в специализированные центры целесобразно выделять 4 лечебно-эвакуационные группы.

**Ключевые слова:** *дозиметрия, лечебно-эвакуационные группы, лимфоцитарный тест, маршрутизация, медицинская сортировка, медицинская эвакуация, прогнозирование, радиационные аварии, степень тяжести лучевого поражения, чрезвычайные ситуации*

**Конфликт интересов**. Авторы статьи подтверждают отсутствие конфликта интересов

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***Contact information:***
***Artem O. Lebedev*** **–** Jun. Res. Ass. of the Department No. 7
**Address:** 46, Zhivopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (925) 072-60-89
**E-mail:** aolebedev@fmbcfmba.ru

***Контактная информация:***
***Лебедев Артём Олегович*** **–** младший научный сотрудник отдела № 7
**Адрес:** Россия, 420012, г. Москва, ул. Живописная, д. 46.
**Тел.:** +7 (925) 072-60-89
**E-mail:** aolebedev@fmbcfmba.ru

## Introduction

Despite tightening of requirements for protection of industrial facilities of nuclear power industry, actual risk of emergencies remains high. Liquidation of medical and sanitary consequences of large-scale radiation accidents has shown that organization of medical and evacuation measures is a priority task in the complex of measures to minimize accidents. Improvement of such measures is necessary for the early provision of emergency medical aid and optimal routing of the injured to the relevant specialized medical centers. For this purpose, in the advanced stages of medical evacuation, it is necessary to carry out medical triage of those affected by ionizing radiation. This triage has its own characteristics associated with determining the radiation dose and severity of acute radiation sickness. In particular, in the absence of data from individual dosimeters the doctor is forced to make a diagnosis and a triage decision based on clinical and hematological indicators — biological dosimetry.

Among the methods of biological dosimetry, the lymphocyte test is widely used because lymphocytes are the most radiologically sensitive blood cells available for analysis [1]. Strict correlation between radiation dose in the range of 1-10 Gy and the number of dead cells allows to use laboratory data on the number of lymphocytes in peripheral blood as a criterion for evaluation of acute radiation disease severity during first 7 days after irradiation [1-10]. The necessity of distinguishing the groups of patients according to the severity of acute radiation disease allows to create so called "medical-tactical corridor". The boundaries of this corridor define the main, most difficult for treatment, group of patients with acute radiation sickness of moderate and high severity.

Empirical dependence of the number of lymphocytes in blood tests on the radiation dose received in the first week after the injury has already been considered in various works [1, 4]. However, they deal with the dependence of only some averaged characteristics without taking into account uncertainty of results of lesion by dose of ±2 Gy. This uncertainty is due to natural biological variability. In isolated use of the lymphocyte test it allows only a very rough estimation of radiation injury severity at the level of statistically averaged values. The influence of radiation intensity (dose rate) was not taken into account in the aforementioned studies. However, the distribution of dose over time can affect the effects of exposure. In this paper we tried to establish the influence of dose rate on the prognostic assessment of acute radiation disease severity by the lymphocyte test, to identify the best correlations and to propose medical triage criteria in order to determine the routing of medical evacuation.

**The aim of the study** was to validate the lymphocyte test method for predicting the severity of acute radiation injury with assessment of the effect of dose rate.

**Materials and methods of the study.** The data for the analysis were taken from the registry of acute radiation injuries in humans of the State Research Center — A.I. Burnazyan Federal Medical Biophysical Center, Federal Medical and Biological Agency of Russia. Correlational analysis of laboratory data on the concentration of lymphocytes in the peripheral blood of the injured from the third day to the sixth day after exposure was used as the method of study. In previous studies we found that in this period the correlation coefficient between lymphocyte concentration and radiation dose was the highest. As a parameter of dose rate in the 1st and 2nd groups we took the "average dose rate during irradiation" (Gy/h) used for analysis in the works [10-13].

The study included clinical and dosimetric data of patients (n=65) involved in the Chernobyl nuclear power plant accident in 1986 and data on patients (n=19) involved in other radiation accidents with gamma-neutron radiation in the former USSR. Only cases with known duration of exposure and low lymphocyte concentration in peripheral blood in the first 24 hours after exposure — less than $1.0\times10^9$/l — were selected from the registry. The data for the analysis are given in Table 1.

Depending on the conditions of irradiation, the affected patients were divided into 3 groups:

— Group 1 (n=32) — Chernobyl accident victims with dose rate less than 2 Gy/h;

— Group 2 (n=33) — Chernobyl accident victims with a dose rate of more than 2 Gy/h;

— Group 3 (n=19) — victims of radiation incidents with a neutron component of radiation in the former USSR — in such incidents high-intensity irradiation of victims occurs in the first seconds.

**Results of the study and their analysis.** We revealed a correlation between the average lymphocyte count in peripheral blood samples taken from day 3 to 6 after exposure

*Таблица 1/ Table No.1*

**Клинико-дозиметрические и лабораторные данные пораженных в радиационных авариях**

Clinical, dosimetric and laboratory data of people affected in radiation accidents

| УКН* UKN code* | Степень тяжести ОЛБ ARS severity | D, Гр D, Gy | Количество лимфоцитов, абс.** Lymphocytes count, abs** | УКН UKN code | Степень тяжести ОЛБ ARS severity | D, Гр D, Gy | Количество лимфоцитов, абс. Lymphocytes count, abs. | УКН UKN code | Степень тяжести ОЛБ ARS severity | D, Гр D, Gy | Количество лимфоцитов, абс. Lymphocytes count, abs. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Пораженные при аварии на ЧАЭС / Injured in the Chernobyl accident, 1986 | | | | | | | | | | | |
| 1001 | IV | 7,5 | 0,08 | 1025 | IV | 6,0 | 0,27 | 1053 | II | 2,8 | 0,81 |
| 1002 | IV | 10,0 | 0,14 | 1026 | IV | 14,0 | 0,10 | 1054 | II | 3,6 | 0,68 |
| 1003 | IV | 10,0 | 0,04 | 1027 | III | 9,3 | 0,24 | 1055 | II | 5,3 | 0,81 |
| 1004 | IV | 13,2 | 3,25 | 1028 | IV | 7,3 | 0,26 | 1056 | II | 3,6 | 0,57 |
| 1005 | III | 5,2 | 0,24 | 1029 | IV | 9,8 | 0,22 | 1057 | II | 3,0 | 0,57 |
| 1006 | IV | 8,5 | 0,30 | 1030 | III | 6,4 | 0,39 | 1058 | II | 3,0 | 0,57 |
| 1007 | III | 5,5 | 0,35 | 1031 | III | 7,7 | 0,35 | 1059 | II | 5,8 | 0,42 |
| 1008 | IV | 9,4 | 0,22 | 1032 | II | 4,2 | 0,59 | 1060 | III | 6,1 | 0,58 |
| 1009 | IV | 10,7 | 0,12 | 1033 | II | 3,9 | 0,39 | 1061 | II | 4,4 | 0,58 |
| 1010 | IV | 12,4 | 0,03 | 1034 | III | 6,7 | 0,33 | 1062 | III | 7,0 | 0,45 |
| 1011 | III | 6,3 | 0,25 | 1035 | II | 4,0 | 0,88 | 1063 | I | 1,1 | 0,48 |
| 1012 | IV | 10,4 | 0,14 | 1037 | II | 2,8 | 0,75 | 1064 | I | 1,0 | 0,91 |
| 1013 | III | 6,3 | 0,24 | 1039 | II | 4,3 | 0,57 | 1065 | II | 3,1 | 0,78 |
| 1014 | IV | 12,2 | 0,11 | 1040 | I | 1,7 | 0,89 | 1066 | II | 1,0 | 0,76 |
| 1015 | IV | 10,0 | 0,14 | 1041 | II | 3,1 | 0,66 | 1067 | II | 2,6 | 0,39 |
| 1016 | IV | 11,3 | 0,11 | 1042 | III | 6,3 | 0,45 | 1068 | III | 4,6 | 0,62 |
| 1023 | IV | 15,2 | 0,05 | 1043 | II | 4,7 | 0,58 | 1070 | II | 1,2 | 0,62 |
| 1018 | II | 2,7 | 0,34 | 1044 | I | 3,7 | 0,83 | 1071 | III | 5,4 | 0,53 |
| 1019 | III | 4,6 | 0,26 | 1047 | III | 3,2 | 0,53 | 1072 | III | 3,6 | 0,67 |
| 1020 | IV | 13,8 | 0,13 | 1048 | I | 2,0 | 1,62 | 1051 | II | 1,8 | 0,51 |
| 1021 | III | 4,7 | 0,34 | 1049 | II | 2,1 | 0,55 | 1103 | I | 1,9 | 0,84 |
| 1022 | III | 7,1 | 0,24 | 1050 | II | 3,3 | 0,40 | 1090 | I | 1,2 | 0,42 |
| 1024 | IV | 2,3 | 0,31 | 1052 | III | 4,3 | 0,35 | 1140 | I | 0,3 | 1,65 |
| 1135 | I | 0,3 | 1,87 | 1091 | I | 1,2 | 1,41 | 1105 | I | 1,5 | 0,79 |
| 1083 | I | 1,9 | 0,76 | 1092 | II | 2,7 | 0,63 | 1106 | I | 2,3 | 0,66 |
| 1084 | I | 1,1 | 1,28 | 1094 | III | 3,6 | 0,47 | 1107 | I | 0,7 | 4,0 |
| 1085 | II | 3,3 | 0,55 | 1095 | II | 2,2 | 0,58 | 1108 | II | 2,3 | 0,67 |
| 1087 | III | 3,5 | 0,95 | 1096 | II | 3,7 | 0,47 | 1115 | I | 0,7 | 2,53 |
| 1088 | II | 2,7 | 2,29 | 1097 | I | 1,0 | 4,87 | 1121 | I | 0,8 | 1,36 |
| 1089 | II | 1,7 | 2,36 | 1098 | I | 2,0 | 3,22 | 1123 | II | 4,3 | 0,81 |
| 1085 | II | 3,3 | 0,55 | 1099 | II | 5,6 | 0,97 | 1129 | II | 4,0 | 0,60 |
| 1087 | III | 3,5 | 0,95 | 1100 | I | 2,6 | 0,94 | 1131 | I | 3,7 | 0,77 |
| 1088 | II | 2,7 | 2,29 | 1101 | II | 3,2 | 0,68 | – | – | – | – |
| 1089 | II | 1,7 | 2,36 | 1102 | I | 1,2 | 3,63 | – | – | – | – |
| Пораженные при инцидентах с облучением гамма-нейтронным излучением /Victims of gamma-neutron irradiation incidents | | | | | | | | | | | |
| 3009 | III | 5,4 | 0,07 | 3010 | I | 0,9 | 1,00 | 3047 | IV | 14,0 | 0,10 |
| 3031 | IV | 10,0 | 0,07 | 3043 | I | 3,0 | 0,50 | 3073 | III | 5,0 | 0,14 |
| 3037 | II | 3,7 | 0,28 | 3045 | I | 5,5 | 0,55 | 3079 | I | 2,1 | 1,07 |
| 3108 | I | 2,4 | 0,74 | 3008 | III | 3,8 | 0,27 | 3030 | II | 3,6 | 0,35 |
| 3032 | IV | >10,0 | 0,03 | 3042 | III | 4,1 | 0,27 | 3036 | II | 3,3 | 0,49 |
| 3046 | IV | 7,4 | 0,08 | 3025 | II | 2,5 | 0,34 | 3071 | I | 3,7 | 0,66 |
| 3011 | I | 0,5 | 0,99 | – | – | – | – | – | – | – | – |

* УКН – Уникальный код пациента из базы данных по острым лучевым поражениям человека ФМБЦ им. А.И.Бурназяна / Unique code of the patient from the database of acute radiation lesions of A.I. Burnazyan Federal Medical and Biological Center

** Среднее значение количества лимфоцитов в периферической крови в период с третьих по 6-е сутки после облучения / Average peripheral blood lymphocyte count from 3 to 6 days after irradiation

and the radiation dose only for groups 1 and 3 under study (Figure). There was greater variability in the data for Group 2 (with low dose rate ≤2 Gy), and in this case we cannot demonstrate any clear dependence. The data of the 2nd group, in particular, are satisfactorily approximated by the following logarithmic function:

$D = -4.59 \ln (C_{lymph}) + 2.01$ (1),

where $D$ — dose, $Gy$; $C_{lymph}$ — average value of lymphocyte count in peripheral blood for the period from the third to the sixth day after irradiation ($\times 10^9$/l).

To understand the uncertainty in assessing the dose and severity of radiation injury by lymphocyte concentration, all data were grouped (Table 2).

Comparison of the data in the figure and in Table 2 shows the effect of the dose rate on the prognosis of the radiation injury severity. It can be seen that in the 1st group the radiation dose received was lower than in the 2nd group with the same lymphocyte counts. Accordingly, the probability of the severity of the developing acute radiation disease in Group 2 was more high.

*Таблица 2/Table No. 2*

**Оценка неопределенности прогноза полученной дозы и степени тяжести лучевого поражения по концентрации лимфоцитов в периферической крови в 1-й – 3-й группах**

Assessment of the uncertainty in the prediction of the received dose (Gy) and the severity of radiation injury from the concentration of lymphocytes in the peripheral blood in groups 1 to 3

| Концентрация лимфоцитов ( $10^9$/л) Lymphocytes concentration ( $10^9$/l) | Усредненная оценка дозы облучения (Гр) / диапазон дозы облучения / прогнозная оценка степени тяжести ОЛБ Averaged estimate of radiation dose (Gy) / range of radiation dose / predictive estimate of ALS severity | | |
|---|---|---|---|
| | 1-я группа – пораженные при аварии на ЧАЭС с мощностью дозы менее 2 Гр/ч Group 1 – affected by the Chernobyl accident with a dose rate of less than 2 Gy/h | 2-я группа – пораженные при аварии на ЧАЭС с мощностью дозы более 2 Гр/ч Group 2 – affected by the Chernobyl accident with a dose rate of more than 2 Gy/h | 3-я группа – пораженные гамма-нейтронным излучением Group 3 – victims of gamma-neutron radiation |
| Менее 0,2 | – | IV | III-IV |
| 0,3 | – | 7,5 (6,0-9,0) IV | 3,9 (2,7-5,1) II-III |
| 0,4 | 4,1 (2,1-6,0) II-III | 6,2 (4,7-7,7) III-IV | 3,3 (2,1-4,5) II-III |
| 0,5 | 3,6 (1,0-5,5) I-III | 5,2 (3,7-6,7) II-IV | 3,0 (1,8-4,2) I-III |
| 0,6 | 3,1 (1,0-5,0) I-III | 4,4 (2,9-5,9) II-III | 2,7 (1,5-3,9) I-II |
| 0,8 | 2,6 (1,0-4,5) I-II | 3,0 (2,0-4,5) II-III | 2,2 (1,0-3,4) I-II |
| 1,0 | 2,1 (0,7-4,0) до II<br>2,1 (0,7-4,0) to II | до II<br>up to II | 1,8 (0,6-3,0) до II<br>1,8 (0,6-3,0) to II |

At a lymphocyte concentration of 0.4-0.8×$10^9$/l at high dose rate ($P_0$>2 Gy/h), its assessment by the lymphocyte test is higher than at low dose rate ($P_0$≤2 Gy/h), by an average of 40.0%. At lymphocyte levels above 0.8×$10^9$/l, dose prognosis becomes more uncertain in all three groups. When peripheral blood lymphocyte counts fall to less than 0.4×$10^9$/L, the average dose estimate is more than 4.0 Gy for Groups 1 and 2. This corresponds to a severe or extremely severe degree of acute radiation sickness. Thus, the most accurate prognosis according to the lymphocyte test is possible in the range of lymphocyte concentrations of 0.4-0.8×$10^9$/l.

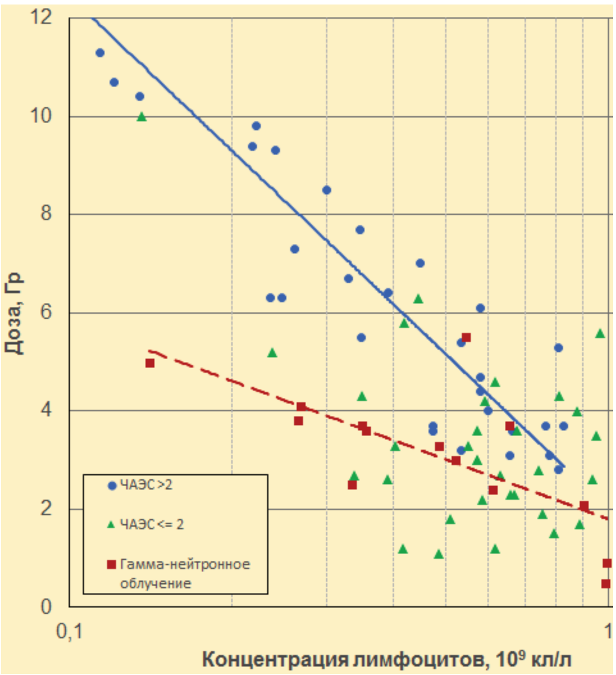


**Рисунок.** Зависимость среднего значения количества лимфоцитов в периферической крови в период с третьих по 6-е сутки после облучения от накопленной дозы облучения. Обозначения: треугольник зеленого цвета – данные 1-й группы; сплошная синяя линия – линия тренда по данным 2-й группы; пунктирная красная линия – линия тренда по данным 3-й группы

**Figure.** Dependence of the average number of lymphocyte count in the peripheral blood on the accumulated dose of irradiation from 3 to 6 days after irradiation. Note: green triangles — data of the 1st group; solid blue line — trend line in the data of the 2nd group; dashed red line — trend line in the data of the 3rd group

Independent estimates for former radiation accident victims, made without regard to radiation intensity, give an average dose estimate 30.0% lower than for "Chernobyl" patients irradiated at low dose rates ($P_0$≤2 Gy/h).

The predicted degree of severity of radiation injuries with the presence of neutron component of radiation — with lymphocyte concentrations less than 1.0×$10^9$/l — is lower compared to the predictions based on the data on the Chernobyl victims. Moreover, the difference in dose estimates progressively increases with decreasing lymphocyte counts. This result contradicts the conclusions of R.E.Goans, E.C.Holloway, M.E.Berger, R.C.Ricks, whose work declares that the lymphocyte test is insensitive to the gamma-neutron radiation spectrum [1].

Thus, it is necessary to assess the severity of radiation injuries according to the lymphocytic test, taking into account the intensity of irradiation. In this case the following typical medical and tactical solution is proposed.

The patients with lymphopenia in the range of 0.4-0.8×$10^9$/l who received acute high-intensity irradiation are the first to be evacuated from Level 1 – Level 2 medical treatment facilities to Level 3 medical treatment facilities. These patients constitute a difficult, but potentially curable group of medium and severe patients. In this group, provided rapid initiation of pathogenetic therapy, survival is possible.

The second line is to evacuate those affected with lymphopenia in the range above 0.8-1.0×$10^9$/l. Within these values, the dose prognosis becomes more uncertain. Therefore, dose estimates and prognosis should be reviewed over several days in order to identify patients with moderate severity of acute radiation sickness in a timely manner.

Those affected with a lymphocyte count above 1.0×$10^9$/l are classified as easily affected. Their treatment does not require the use of specialized methods and therefore they can be left in level 2 medical institutions.

Those affected with lymphopenia less than 0.4×$10^9$/l — irrespective of the conditions of exposure — are evacuated to Level 3 medical treatment organizations in the second line. When there is a mass admission of patients affected by ionizing radiation and under conditions of a heavy workload of medical treatment organizations on the evacuation route such patients are not evacuated. They are given symptomatic care, since their survival is unlikely, even if pathogenetic therapy is started in time.

**Conclusion**

Uncertainty in dose estimation for conditions of irradiation with high dose rate ($P_0$>2 Gy/h) can reach (±1.0-1.5) Gy. It means that in the first approximation the lymphocyte test is of practical prognostic value in the range of lymphocyte concentrations from 0.4-0.8×$10^9$/l at high dose rate. When lymphocyte concentration is less than 0.4×$10^9$/l, acute radiation syndrome of extremely grave degree is predicted with high confidence. At low dose rates ($P_0$≤2 Gy/h) the prognosis is highly uncertain in the range of lymphocyte concentrations above 0.6×$10^9$/l. In such cases, the estimated dose is 1-4 Gy, which corresponds to mild to moderate severity of acute radiation sickness.

The identified dependencies can be used for medical triage of the injured in the advanced stages of medical evacuation, in order to adjust their routing to specialized medical centers. Thus, the following criteria should be used for mass loading of medical treatment facilities in the accident zone:

— when peripheral blood lymphocyte concentration is less than 0.4×$10^9$/l under any exposure conditions, acute radiation sickness of severe and extremely severe degree is predicted; such patients can be referred to the "agonizing" group;

— in the range of lymphocyte concentrations 0.4-0.8×$10^9$/l the assessment of dose and severity of acute radiation disease under high dose rate conditions is most accurate. These patients are referred to the category of moderate severity, whose treatment should be started as soon as possible in a specialized hospital — a level 3 medical treatment organization;

— peripheral blood lymphocyte concentrations in the range of 0.8-1.0×$10^9$/l predicts mild acute radiation sickness — those affected may be temporarily left for treatment in a Level 1 or Level 2 medical facility with daily adjustments of clinical and laboratory data and prognosis;

— If peripheral blood lymphocyte concentration is higher than 1.0×$10^9$/l, acute radiation sickness stage I is predicted.

This paper is the first to analyze the dependence of lymphocyte concentration on accumulated dose for cases with gamma-neutron irradiation compared to similar data on those affected by the Chernobyl accident. With the same values of lymphocytes, the predicted severity of acute radiation sickness is lower.

The lymphocyte test is appropriate when information about individual exposure conditions and the results of dose assessment by other methods of biological dosimetry are available.

It should be noted that in the victims of radiation accidents with hypovolemia, against the background of infusion and transfusion therapy, overestimation of the informativeness of some hematological parameters, including the number of lymphocytes, is possible. Therefore, when making a preliminary diagnosis, relying only on the lymphocyte test without taking this factor into account can lead to overdiagnosis. These peculiarities require dynamic control of laboratory parameters.

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***Original article***



# COMPARISON OF THE RISK OF MORTALITY FROM SOLID CANCERS AFTER RADIATION INCIDENTS AND OCCUPATIONAL EXPOSURES

A.N.Koterov[1.], L.N.Ushenkova[1.], M.V.Kalinina[1.], A.P.Biryukov[1.]

[1.] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** .The purpose of the study was to compare the excess relative risk of mortality (ERR per 1 Sv) from solid cancers during acute — catastrophic or accidental and occupational, fractionated or chronic — exposure.
Study materials and methods. Materials of the study: maintained database (source database) on nuclear industry workers from about 40 countries, based on which a pooled analysis of data was conducted to determine the integral value of ERR per 1 Gy for mortality from solid cancers; indicators of cohorts exposed to catastrophic and accidental radiation: the cohort LSS victims of the atomic bombings in Japan; residents of the Techa River — radioactive contamination resulting from releases from "Mayak" production association; Russian liquidators of the Chernobyl nuclear accident.
Study results and analysis. Comparison of the ERR of 1 Sv deaths from solid cancers for workers in the global nuclear industry (pooling analysis of data from 37 studies) with those of the LSS cohort; Techa River residents and Chernobyl accident liquidators showed no logical and principled differences, with the risks for the latter two cohorts being the highest.
Although the findings partly support the approach of the UN Scientific Committee on the Effects of Atomic Radiation that the carcinogenic effects of acute (catastrophic or accidental) and occupational (fractionated or chronic) radiation exposure are independent of the dose rate factor (DDREF), this issue cannot be considered unequivocally resolved, given the biological mechanisms and radiobiological experimental data.
Based on the ERR per 1 Sv, the average external dose, and the annual background cancer mortality rates in Russia and the United States, the expected cancer mortality increase for 100,000 workers in the nuclear industry would be an average of 32-69 people over 10 years — 0.032-0.069% of the group. Such risks, due to multiple carcinogenic non-radiation factors of life and work, as well as fluctuating background values, cannot be taken into account in the practice of disaster medicine and public health.

**Key words:** *atomic bomb victims, catastrophic exposure, Chernobyl accident liquidators, chronic exposure, emergency exposure, fractionated exposure, mortality risk, nuclear industry workers, solid cancers, Techa River residents*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***



# СРАВНЕНИЕ РИСКА СМЕРТНОСТИ ОТ СÓЛИДНЫХ РАКОВ ПОСЛЕ РАДИАЦИОННЫХ ИНЦИДЕНТОВ И ПРОФЕССИОНАЛЬНОГО ОБЛУЧЕНИЯ

А.Н.Котеров[1], Л.Н.Ушенкова[1], М.В.Калинина[1], А.П.Бирюков[1]

[1.] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** *Цель исследования* – сравнение избыточного относительного риска смертности (ERR на 1 Зв) от сóлидных раков при остром – катастрофическом или аварийном и профессиональном – фракционированном или хроническом – облучении.
*Материалы и методы исследования.* Материалы исследования: поддерживаемая база данных (база источников) по работникам ядерной индустрии из примерно 40 стран, на основе которой проведен объединяющий анализ данных для определения интегральной величины ERR на 1 Гр по смертности от сóлидных раков; показатели когорт, подвергавшихся катастрофическому и аварийному облучению: когорта LSS пострадавших от атомных бомбардировок в Японии; резиденты реки Теча – радиоактивное загрязнение в результате выбросов ПО «Маяк»; российские ликвидаторы аварии на Чернобыльской АЭС.
*Результаты исследования и их анализ.* Сравнение величины ERR смертности от сóлидных раков на 1 Зв для работников мировой ядерной индустрии (объединяющий анализ данных 37 исследований) с показателями когорты LSS; резидентов на реке Теча и ликвидаторов аварии на Чернобыльской АЭС – продемонстрировало отсутствие поддающихся логике и принципиальных отличий, причем риски для двух последних когорт были наиболее высокими.
Хотя полученные данные отчасти подтверждают подход Научного комитета по действию атомной радиации ООН, согласно которому канцерогенные эффекты острого (катастрофического или аварийного) и профессионального (фракционированного или хронического) лучевых воздействий не зависят от фактора мощности дозы (DDREF), тем не менее, с учетом биологических механизмов и данных радиобиологических экспериментов, этот вопрос не может считаться однозначно решенным.
Исходя из ERR на 1 Зв, из средней дозы внешнего облучения, а также из величины ежегодной фоновой смертности от рака в России и США ожидаемая прибавка смертности от раков для 100 тыс. работников ядерной индустрии составит в среднем 32–69 чел. за 10 лет – 0,032–0,069% от группы. Подобные риски, в связи со множеством канцерогенных нелучевых факторов жизни и работы, равно как и с колебаниями фонового значения, невозможно учитывать в практике медицины катастроф и здравоохранения.

**Ключевые слова:** *аварийное облучение, катастрофическое облучение, ликвидаторы аварии на Чернобыльской АЭС, пострадавшие от атомных бомбардировок, работники ядерной индустрии, резиденты реки Теча, риск смертности, сóлидные раки, фракционированное облучение, хроническое облучение*

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***Contact information:***
***Aleksey N. Koterov*** **–** Dr. Sc. (Biol.); Head of the Laboratory
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (499) 190-96-37
**E-mail:** govorilga@inbox.ru

***Контактная информация:***
***Котеров Алексей Николаевич*** **–** доктор биологических наук; заведующий лабораторией
**Адрес:** Россия, 123098, Москва, ул. Живописная, 46
**Тел.:** +7 (499) 190-96-37
**E-mail:** govorilga@inbox.ru

Introduction. The problem of comparing medico-biological effects of acute exposure, including accidental irradiation and irradiation after nuclear accidents, with the effects of fractionated and chronic exposure has arisen since the first stages of the formation and development of radiation disciplines [1, 2]. It has been repeatedly found in experiments that the yield of various effects of radiation exposure decreases depending on the level (rate) of dose, since cells "have time" to recover from sublethal damage [3].

The fact that dose and dose-rate-effectiveness factor (DDREF) influences on the biological effects of irradiation is not questioned. However, discussions on the extent to which DDREF accounting can be reflected in epidemiological risk assessments have been going on for a long time [4-7]. Previously, international organizations (the UN Scientific Committee on the Effects of Radiation — UNSCEAR; the International Commission on Radiation Protection — ICRP) used a DDREF of two to study chronic exposure to radiation with low linear energy transfer (LET). That is, the effectiveness of acute exposure had to be divided by 2 [3, 7, 8].Thus, only the dose rate factor, i.e., DREF, was taken into account. At the same time, BEIR-VII, a periodic document of the US Academy of Sciences Committee on Radiation Effects, states that DDREF also depends on dose. It varies from 1.5 to 3 for different solid cancers in the Japanese Life Span Study (LSS) cohort of atomic bombing victims and different experimental models [4, 9, 10].

The question of the role of DDREF has been complicated by studies of the incidence of carcinogenic effects in a combined cohort of nuclear industry workers from 15 countries — E. Cardis et al. (2005-2008) — [11-13]. Based on these data, UNSCEAR concluded that the previous DDREF value of two was "very high" for nuclear industry workers. Therefore, the risk at low doses can be estimated by linear extrapolation from the risk for the LSS cohort without applying the DDREF factor, i.e., DDREF = 1 [14, 15].

Thus, a comparison of the incidence of cancer and leukemia in the pooled cohort of nuclear industry workers with the considered reference value for the LSS cohort has in part already been done. But its results have never led international organizations to a definitive conclusion as to which value should be used for chronic or prolonged occupational exposures. So there are still discussions on this issue [4, 5, 8-16]. In addition, the already mentioned studies by E. Cardis et al. in 2005-2008 were criticized for the non-homogeneity of the cohort, in which the main contribution to the increase of carcinogenesis frequency was made by Canadian workers [4, 11-13, 17, 18].

Our maintained database (source database) on biomedical and epidemiological effects in workers in about 40 countries has about 1,000 papers and documents. Therefore, we have been able to combine a considerable amount of data on Excess relative risks (ERR) of cancer per unit dose (1 Sv) for workers in major nuclear-industry countries. As a result, we obtained a certain integral value characterizing the risk for the category "world nuclear industry workers per se”. This can be important in comparing the effects in different categories of workers dealing with radiation exposure. The sample included both individual studies and all pooled analyses performed to date — see below.

**Purpose of the study** was to summarize the data on ERR per 1 Sv for the world cohort of nuclear industry workers (fractionated and chronic exposure) followed by comparison of the obtained value with the table value of this parameter: for the LSS cohort, whose radiation exposure was acute and catastrophic; for residents of the Techa River — radioactive contamination from “Mayak” Industrial Association and for liquidators of the Chernobyl NPP accident. On the basis of the results obtained, the excess absolute risk of cancer for workers in the nuclear industry was also assessed.

**Materials and methods of research.** Sources in the available database with publications and documents related to biomedical effects in employees of the nuclear industry in different countries of the world. ERR per 1 Sv was analyzed for the incidence of mortality from solid cancers — ERR = RR -1, where RR is the relative risk [9]. A number of studies used ERR values per 0.1 Sv — such data were excluded. In addition, studies in uranium mine workers were not included in the analysis.

Typically, sample processing in synthetic studies (review, meta-analysis, and pooled analysis, including simple pooling) involves assessing their heterogeneity and eliminating outlier values [19, 20]. In the presented study, the sample was evaluated for normality of distribution, central tendencies, and outliers using Statistica, ver. 10. The forest-plot was also plotted using this program. Outlier values were determined using Chauvenet's criterion (table up to 50-1000 variants) [21].

**Results of the study and their analysis.** Currently, not all of the publications in our database of sources have been analyzed, but we managed to collect 37 studies from 6 countries, as well as international papers that provided data for the final ERR per 1 Sv for mortality from solid cancers (Table 1, Figure). A visual illustration summarizing all samples and data is the corresponding forest-plot (with ERR = 0 – no risk).

Table 1 and the figure show that the risk for workers from different industries and different countries varies greatly — the highest values were found for the Canadian cohort and

*Таблица 1 /Table No.1*

**ERR на 1 Зв смертности от сóлидных раков для работников мировой ядерной индустрии**

Excessive relative risk of death from cancer (ERR per 1 Sv) for world nuclear workers

| Когорта / Cohort | ERR на 1 Зв -90%-й CI*<br>ERR per 1 Sv –90% CI* | Источник<br>Source |
|---|---|---|
| **Великобритания / United Kingdom** | | |
| АЭС UKAWE / UKAWE NPP | 7,6 (0,4; 15,3) | Beral V., et al., 1988 [22] |
| АЭС UKAEA / UKAEA NPP | 0,8 (–1,0; 3,1) | Fraser P.L., et al., 1993 [23] |
| Обогащение урана Capenhurst<br>Capenhurst uranium enrichment | 1,3 (0; 2,4) | McGeoghegan D., et al., 2000 [24] |
| АЭС Sellafield / Sellafield NPP | 0,11 (–0,4; 0,8) | Douglas A.J., et al., 1994 [25] |
| Производство ядерного топлива Springfields<br>Springfields nuclear fuel production | 0,64 (–0,95; 2,7) | McGeoghegan D. Et al., 2000 [24] |
| UK National Registry for Radiation Workers 1976–1988 | 0,47 (–0,12; 1,2) | Kendall, et al. 1992 [26], Russ A. Et al., 2006 [27] |
| Производство ядерного топлива British Nuclear Fuels (BNFL)<br>British Nuclear Fuels (BNFL) nuclear fuel production | 0,29 (0,02; 0,59) | Gillies M, Haylock R., 2014 [28] |
| National Registry for Radiation Workers | 0,28 (0,06; 0,53) | Haylock R.G.E., et al., 2018 [29] |
| То же / Ibid | 1,42 (0,51; 2,38); исключены данные для доз свыше 0,1 Гр / 1.42 (0.51; 2.38); data for doses above 0.1 Gy are excluded. | Haylock R.G.E., et al., 2018 [29] |
| **Канада / Canada** | | |
| АЭС AECL / AECL NPP | 0,049 (–0,68; 2,17) | Gribbin M.A., et al., 1993 [30] |
| То же / Ibid | 2,37 (–0,37, 6,60) | Zablotska L.B., et al., 2014 [31] |
| То же / Ibid | 1,20 (–0,73, 4,33); коррекция на дозы, социоэкономический статус и др.<br>1.20 (-0.73, 4.33); correction for doses, socioeconomic status, etc. | Zablotska L.B., et al., 2014 [31] |
| The National Dose Registry (NDR) of Canada | 3,0 (1,1; 4,9); только мужчины (женщины – нет эффекта)<br>3.0 (1.1; 4.9); men only (women – no effect) | Ashmore J.P. et al., 1991; 1997 [33, 36], Zielinski J.M. et al., 2008 [34] |
| То же / Ibid | 2,6 (1,3; 4,3); только мужчины (для женщин выборка мала)<br>2.6 (1.3; 4.3); men only (too small sample for women) | Sont W.N. et al., 2001 [35], Zielinski J.M., et al., 2008 [34] |
| Канадские работники АЭС (AECL) в объединенном исследовании трёх стран (по данным [37])<br>Canadian nuclear power plant workers (AECL) in a combined 3-country study (based on [37]) | 0,13 (<0; 2,1) | Cardis E., et al., 1995 [36], Ashmore J.P., et al., 2007 [37] |
| Канадские работники АЭС (AECL) workers в объединенном исследовании 15 стран (по данным [37])<br>Canadian nuclear power plant (AECL) workers in a pooled study of 15 countries (based on [37]) | 6,65 (2,56; 13,00) | Cardis E., et al., 2007 [12], Ashmore J.P., et al., 2007 [37] |
| То же** / Ibid** | 3,60 (1,03; 7,27) | Cardis, 2007 [12], Vrijheid, et al., 2008 [13] |
| **США / USA** | | |
| X-10 workers | 1,45 (0,15; 3,48) | Wing S., 1991 [38] |
| Hanford Nuclear Reservation | 3,24 (0,80; 6,17) | Wing S., Richardson D.B., 2005 [39] |
| Производство ядерного оружия Rocky Flats / Rocky Flats nuclear weapons production | –0,04 (–1,7; 1,25) | Gilbert E.S., et al., 1993*b* [40] |
| Oak Ridge National Laboratory (ORNL) | 1,5 (0,2; 3,5) | Frome E.L., et al. 1997 [41], Russ A., et al., 2006 [27] |
| То же / Ibid | 4,28 (95% CI: –0,40, 11,6) | Ashmore J.P., et al., 2007; 2010 [37, 42] |
| **Франция / France** | | |
| Объединенная когорта работников ядерной индустрии Франции<br>United cohort of French nuclear industry workers | 0,34 (–0,56; 1,38) | Metz-Flamant C., et al., 2013 [43] |
| Работники ядерной индустрии Франции (CEA, AREVA NC и EDF)<br>Employees of the French nuclear industry (CEA, AREVA NC and EDF) | 0,34 (–0,44; 1,24) | Fournier L., et al., 2018 [44] |
| То же / Ibid | 0,37 (–0,44; 1,30) | Leuraud K., et al., 2017 [45] |
| **Россия / Russia** | | |
| Работники Institute of Physics и Power Engineering (IPPE)<br>Workers of the Institute of Physics и Power Engineering (IPPE) | 0,22 (95% CI: –4,22; 7,96) | Ivanov V.K., et al., 2004; 2006 [46] |
| Работники ПО «Маяк»<br>Workers of "Mayak" production association | 0,3 (0,2; 0,4); для lag-периода 20 лет<br>0.3 (0.2; 0.4); for a lag period of 20 years | Shilnikova N.S., et al., 2003 [47] |

| Когорта / Cohort | ERR на 1 Зв -90%-й CI*<br>ERR per 1 Sv –90% CI* | Источник<br>Source |
|---|---|---|
| **Япония / Japan** | | |
| Регистр работников ядерной индустрии<br>Nuclear industry workers Registry | 1,26 (95% CI: –0,27, 3,00) | Akiba S., Mizuno S., 2012 [48] |
| То же / Ibid | 0,38 (–0,84; 1,81); с поправкой на курение, lag-период 15 лет<br>0.38 (-0.84; 1.81); adjusted for smoking, lag period of 15 years | Kudo S.. et al., 2018 [49] |
| **Объединенные когорты / Combined cohorts** | | |
| Объединенный анализ работников ядерной индустрии Канады<br>Combined analysis of Canada nuclear industry workers | 2,80 (–0,038; 7,13) | Zablotska L.B., et al., 2004 [50] |
| Объединенный анализ работников ядерной индустрии Великобритании<br>Combined analysis of United Kingdom nuclear industry workers | –0,02 (–0,5; 0,6) | Carpenter L., et al., 1994; 1998 [51, 52] |
| Объединенный анализ работников ядерной индустрии Великобритании (NRRW)<br>Combined analysis of United Kingdom nuclear industry workers (NRRW) | 0,086 (–0,28; 0,52) | Muirhead C.R., et al., 1999 [53] |
| | 0,275 (0,02; 0,56) | Muirhead C.R., et al., 2009 [54] |
| Объединенный анализ работников ядерных предприятий США по обогащению топлива<br>Combined analysis of U.S. nuclear enrichment workers | 0,506 (–2,01; 4,64) | Zablotska L.B., et al., 2004 [50] |
| Объединенное исследование работников ядерной индустрии Великобритании, Канады и США<br>Combined study of nuclear industry workers of UK, Canada, USA | –0,07 (–0,39; 0,30) | Cardis E., et al., 1995 [36] |
| Объединенное исследование работников ядерной индустрии 15 стран (Европа – Америка – Восточная Азия)<br>Combined study of nuclear industry workers of 15 countries (Europe – America – East Asia) | 0,87 (0,03; 1,88) | Thierry-Chef M., et al., 2007; Cardis E., et al., 2005; 2007; Vrijheid M., et al., 2007, 2008; [11–13, 55, 56] |
| Объединенное исследование работников ядерной индустрии 14 стран (Европа – Америка – Восточная Азия). То же, что в предыдущем случае, но без Канады<br>Combined survey of nuclear industry workers of 14 countries (Europe – America – East Asia). Same as the previous case, but without Canada | 0,58 (–0,1; 1,39) | Wakeford R., 2014 [17] |
| Объединенное исследование работников ядерной индустрии Франции, Англии и США (INWORK)<br>Joint INWORK study of nuclear industry workers of France, England, and the United States | 0,42; (0,13; 0,73) | Daniels R.D., et al., 2017 [57] |
| То же / Ibid | 0,47; (0,18; 0,79) | Richardson D.B., et al., 2015 [58], Laurier D., et al., 2017 [59] |

* Если не указаны иные CI (CI – доверительные интервалы) / Unless otherwise specified CI (CI – confidence intervals)
** Две различные когорты, вторая – дополненная / Two different cohorts, second augmented

slightly less for the United States. It should be noted that in the works of Ashmore J.P. et al. (2007, 2010) with high values for the United States, the authors presented a value only for the Oak Ridge Nuclear Center [37, 42].

The results of the pooled analysis of the ERR per Sv data for nuclear industry workers compared to the cohorts of victims of nuclear incidents are presented in Table 2.

Table 2 shows that the original sample of 36 studies for all countries — the data from one study were outliers — is heterogeneous. This was shown both by analysis of distribution normality and by comparison of central tendencies: the mean and median are very different. In a pooled analysis of data for 15 countries, Cardis E. et al. (2005-2008), a significant contribution to the distortion of the results was made, as mentioned above, by the data-dropout cohort of Canadian workers [11-13]. Therefore, the above analysis was later corrected in the study of Wakeford R. (2014) by eliminating data for Canada from the sample, resulting in a one and a half fold decrease in the pooled ERR per 1 Sv for workers from 14 countries [17] — see Table 1, Pooled Cohorts. The anomalous nature of the Canadian cohort in terms of cancer mortality risk has been discussed many times, including the fundamental benefits and BEIR-VII [4, 9, 18, 62, 63]. For this cohort, the risk of lung cancer from — probably — non-radiational factors prevailed, including no adjustment for smoking [62, 63]. In addition, the main contributor to the effect was a subgroup from one of the plants with relatively early employment — before 1965. [63].

For this reason, in our pooling analysis, too, data for Canadian workers were excluded from the sample, which became much more homogeneous (cf. mean and median in Table 2), although a completely normal distribution was not achieved.

For comparison with the effect of occupational, i.e., fractionated or chronic, exposure, data on ERR per 1 Sv were taken for cohorts of those affected by radiation incidents. As already noted, the "tabulated" one for radiation risks to date is the Japanese LSS cohort, whose last study (follow-up — 1950-2003) revealed an ERR per 1 Sv equal to 0.42 [4, 5, 8-13, 18, 61-63]. One can see from Table 2 that this value is less than for the residents on the Techa river who suffered from uncontrolled releases from the "Mayak" Industrial

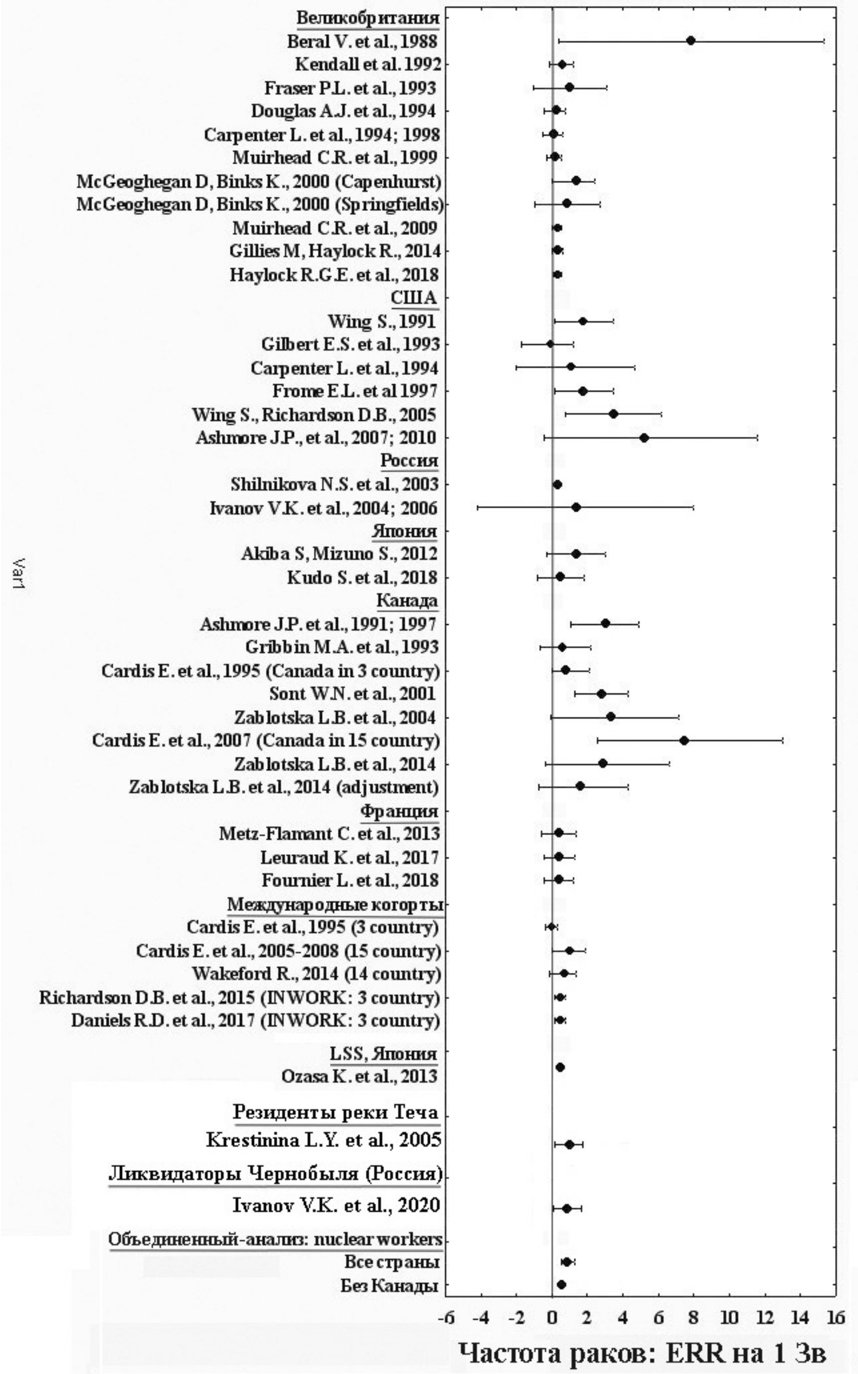


**Рисунок.** Forest-plot подборки источников по ERR на 1 Зв для сóлидных раков (с 90%-ным или 95%-ным CI; см. в табл. 1) для работников ядерной индустрии различных стран вместе с международными исследованиями объединенных когорт. Представлены также данные для когорты LSS пострадавших от атомных бомбардировок в Японии, для резидентов реки Теча, российских ликвидаторов аварии на Чернобыльской АЭС и результаты настоящего объединяющего анализа (нижние строки)

**Figure.** Forest-plot of a set of ERR sources per 1 Sv for solid crayfish (with 90% or 95% CI; see Table 1) for nuclear industry workers from different countries, coupled with international studies of pooled cohorts. Data are also presented for the LSS cohort of atomic bomb victims in Japan, residents of the Techa River, Russian liquidators of the Chernobyl accident, and the results of this merging analysis (bottom lines)

Association in the 1950s and for the Russian liquidators of the Chernobyl accident, the last data of 2020. [60, 61]. The corresponding values were 0.92 and 0.82. It should be said, however, that these 2 cohorts may have been influenced by a mass of uncontrolled intervening factors, resulting in difficulties in detecting true radiation dependencies [64]. For example, the effects of chemical agents, including lead and detergents, as well as the effects of stress and radiophobia in the 1990s, are known for liquidators, often leading to heavy smoking and alcohol abuse [65]. On the other hand, the data for the Japanese LSS cohort as well, with its triply revised dosimetry and with uncertainties in the contribution of neutron exposure, can also be called "report card" only conventionally, since there is nothing more appropriate [62].

Of course, in all the above cases, the control group was chosen within the cohort as the lowest dose group in the ERR calculations. Comparison with the general population is incorrect due to both the healthy worker effect and the clearly

*Таблица 2 /Table No. 2*

**ERR на 1 Зв смертности от сóлидных раков для пострадавших от радиационных инцидентов и работников мировой ядерной индустрии**

ERR per 1 Sv for solid cancer mortality for victims of radiation accidents and for world nuclear workers

| Когорта<br>Cohort | Mean –95% CI | Median –25% и 75% quartile<br>Median –25% and 75% quartile |
|---|---|---|
| LSS [10]* | 0,42 (0,32; 0,53) | – |
| Резиденты реки Теча [60]<br>Techa river residents [60] | 0,92 (0,2; 1,7) | – |
| Российские ликвидаторы аварии на Чернобыльской АЭС [61]<br>Russian liquidators of the Chernobyl accident [61] | 0,82 (0,1; 1,65) | – |
| Работники ядерной индустрии; настоящее исследование (вся выборка; 36 вариантов**)<br>Nuclear industry workers; present study (entire sample; 36 options**) | 1,1 (0,61; 1,58) | 0,47 (0,28; 1,43) |
| Работники ядерной индустрии; настоящее исследование (без Канады; 26 вариантов**)<br>Nuclear industry workers; present study (without Canada; 26 options**) | 0,51 (0,33; 0,69) | 0,38 (0,28; 0,64) |

* Риск к возрасту 70 лет при облучении в возрасте от 30 лет / Risk by the age of 70 with the exposure from the age of 30

** После анализа на выпадающие значения / After analysis for outlier variants

better medical care in the exposed groups. But here one should take into account the possibility of different mentality of those who are in different dose groups [62]. For example, for Japanese workers of the nuclear industry, an association has been shown between the level of absorbed radiation dose, on the one hand, and smoking, as well as alcoholism, on the other. In addition, it turned out that for higher dose groups the frequency of routine diagnostics was lower [66]. There is an association between the radiation dose and the frequency of mortality from nonradiated pathologies (liver cirrhosis, oral and pharyngeal cancer, psychosis, external causes) among French nuclear industry workers — imitation of the "dose — effect" relation by alcohol [67]. All these factors are capable of distorting not only the "dose — effect" association for radiation exposure, but even of changing its character in a qualitative sense, if the radiation doses are not too high.

Nevertheless, it follows from Table 2 that the combined ERR per Sv for solid cancer mortality we obtained for workers in the global nuclear industry after excluding data for Canada is generally comparable to military and accidental radiation incidents. But even here we should take into account that a significant contribution to the frequency of cancers was made by those employed in the nuclear industries of the early 1940's to 1950's [68]. [68].

At the same time, the data we obtained do not provide a strong argument for the rejection by UNSCEAR in recent years of the DDREF coefficient in epidemiological studies of radiation carcinogenesis [14, 15]. Biological mechanisms of radiation effects as well as experimental radiobiological data do not allow one to agree with seemingly implausible conclusions from observational studies of populations with multiple intervening nonradiation factors (confounders) and biases [3, 9, 64]. Of course, the canons of establishing causality in epidemiology and evidence-based medicine are, first, the reliance on data for humans and, second, if clinical experimentation is not possible, on epidemiological and observational, rather than laboratory studies [69-73]. At the same time, some authors point to the fundamental importance of confirming the statistical regularities identified for humans by biological mechanisms, sometimes placing the latter at the forefront of the evidence [74]. Such views, of course, are somewhat marginal from the standpoint of epidemiology basics, but should probably be taken into account in the case of strange epidemiological data [75]. As one of the pioneers of evidence-based methodologies in epidemiology and evidence-based medicine, A.B.Hill, said: one should never "throw common sense out the window" [75-77].

It was of interest both epidemiologically and socially to estimate the absolute increase in the number of solid cancer cases based on the estimated ERR values for workers in the global nuclear industry. In other words, an answer to the question of what is the occupational hazard of this disease.

According to GLOBOSCAN, the average annual incidence of male cancer mortality is 126 deaths per 100,000 people (2012) [78]. In the United States and Russia (Rosstat) this figure is 200 deaths per year (2020) per 100,000 population, which we will take as our baseline. In our pooling study (without Canada), the ERR per Sv is 0.51. Thus, for 100,000 workers in the nuclear industry, if they had received a dose of 1 Sv each over, say, 10 years (~2,000 background cancer deaths), given the resulting risk value, we would expect 1020 additional deaths. However, in fact, there were fewer of them, because the "background" cancer rate for workers of harmful industries is lower than that for the corresponding sex-age group of the general population, because of the "healthy worker effect" [62].

In addition, workers in the nuclear industry did not receive average doses in the order of 1 Sv by the hundreds of thousands. Based on a sample of 63 items in our database of nuclear industry workers, the average individual accumulated external dose ranged from 3.8 mSv (Company NPP, CEA-COGEMA, France; 1946-1994) to 128 mSv (Sellafield NPP, UK; 1947-1988) [11, 25]. According to our calculations, the mean value for all countries and enterprises was 31.1 mSv (95% CI: 24.6 and 37.5) and the median was 24.0 mSv.

In other words, the expected increase in mortality from solid cancers for 100 thousand employees of the nuclear industry with the obtained risk value will be on average 32 persons for 10 years, i.e. 0.032% of the group. Such risks, due to many carcinogenic non-radiation factors of everyday life and work and fluctuations of the background value, cannot be taken into account in the practice of disaster medicine and public health [80]. Even if we assume an ERR value of 1 Sv for the entire original sample, including data for Canada, the conclusion would not change too much: the expected increase in cancer mortality would be 0.069% of the group.

**Conclusions**

1. Comparison of excess relative risk of mortality from solid cancers per unit external dose (per 1 Sv) for nuclear industry workers from different countries (pooling analysis of 37 studies) with corresponding values for atomic bombing vic-

tims in Japan (LSS cohort); for residents on the Techa — radioactive contamination in the 1950s; for liquidators of the Chernobyl accident in Russia — showed no logical and fundamental differences, with the risks for the latter two cohorts being the highest.

2. Although the findings partially support the UNSCEAR approach of recent years, according to which the carcinogenic effects of acute, accident and fractionated or chronic radiation exposure are independent of the dose rate factor (DDREF), nevertheless, taking into account biological mechanisms and data from radiobiological experiments, this question cannot be considered unequivocally resolved.

3. Based on the excess relative risk per Sv obtained in the pooling analysis, on the average accumulated external radiation dose, as well as on the value of the annual background cancer mortality rate in Russia and the USA — the expected increase in mortality from solid cancers for 100 thousand employees of the nuclear industry will be on average 32-69 persons over 10 years — 0.032-0.069% of the group. Such risks — due to the many carcinogenic non-radiation factors of everyday life and work and fluctuating background values — cannot be taken into account in the practice of disaster medicine and public health.

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*Original article*



# CLINICAL AND EPIDEMIOLOGICAL ANALYSIS OF MORBIDITY AND MORTALITY FROM MALIGNANT NEOPLASMS AMONG EMPLOYEES OF RADIATION HAZARDOUS ENTERPRISES AND THE POPULATION LIVING NEAR NUCLEAR INDUSTRY AND NUCLEAR POWER FACILITIES

A.P.Biryukov[1], E.P.Korovkina[1], E.V.Vasilyev[1], Yu.V.Orlov[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** *The purpose of the study* is to analyze the oncoepidemiological situation in the vicinity of nuclear industry and nuclear power plants.
*Materials and methods of the study.* The main materials of the study were the data of official medical statistics for 2012-2018 on the incidence of malignant neoplasms and mortality from them: the contingent of medical treatment organizations of FMBA of Russia in 10 closed administrative-territorial formations of Rosatom State Corporation — a research sample; total contingent served by medical treatment organizations of FMBA of Russia — data of the Federal Center for Extreme Problems Information Technology of FMBA of Russia; population of Russian Federation as a whole.
An in-depth analysis of the morbidity and mortality from malignant neoplasms among employees of enterprises and the population served by medical treatment organizations of FMBA of Russia was performed using data from the Branch Cancer Registry of FMBA of Russia.
*Results of the study and their analysis.* According to the results of the analysis an increase in the incidence of malignant neoplasms was observed in medical treatment organizations of the Federal Medical and Biological Agency of Russia in closed administrative territorial formations, in all medical treatment organizations of the Federal Medical and Biological Agency of Russia, and in the Russian Federation as a whole. In 2012-2018 the incidence of malignant neoplasms (per 100,000 population) was: in closed administrative territorial entities — 412.4 and 526.6 respectively; in all medical treatment institutions of FMBA of Russia — 328.4 and 390.1; in the Russian Federation as a whole — 367.3 and 425.5 respectively.
Analysis of mortality rates from malignant neoplasms showed that in all medical treatment institutions of the Federal Medical and Biomedical Agency of Russia the mortality rate from malignant neoplasms (per 100 thousand population) in this time interval was 149.1 and 167.9 persons respectively, which is significantly lower than the all-Russian rates of 201.0 and 200.0 persons respectively. Mortality from malignant neoplasms in closed administrative territorial units amounted to 220.1 and 257.3 persons respectively, which exceeds both all medical treatment institutions of the Federal Medical and Biological Agency and the Russian Federation as a whole.

**Key words:** *closed administrative-territorial formations, employees of radiation hazardous enterprises, malignant neoplasms, medical treatment organizations, morbidity, mortality rate, population, nuclear industry facilities, nuclear power, nuclear power facilities*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***



# КЛИНИКО-ЭПИДЕМИОЛОГИЧЕСКИЙ АНАЛИЗ ЗАБОЛЕВАЕМОСТИ ЗЛОКАЧЕСТВЕННЫМИ НОВООБРАЗОВАНИЯМИ И СМЕРТНОСТИ ОТ НИХ СРЕДИ РАБОТНИКОВ РАДИАЦИОННО ОПАСНЫХ ПРЕДПРИЯТИЙ И НАСЕЛЕНИЯ, ПРОЖИВАЮЩЕГО ВБЛИЗИ ОБЪЕКТОВ АТОМНОЙ ПРОМЫШЛЕННОСТИ И ЯДЕРНОЙ ЭНЕРГЕТИКИ

А.П.Бирюков[1], Э.П.Коровкина[1], Е.В.Васильев[1], Ю.В.Орлов[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** *Цель исследования* – анализ онкоэпидемиологической ситуации вблизи предприятий атомной промышленности и ядерной энергетики.
*Материалы и методы исследования.* Основными материалами исследования являлись данные официальной медицинской статистики за 2012–2018 гг. о заболеваемости злокачественными новообразованиями (ЗНО) и смертности от них: контингента лечебных медицинских организаций (ЛМО) ФМБА России в 10 закрытых административно-территориальных образованиях (ЗАТО) Госкорпорации «Росатом» – исследовательская выборка; всего контингента, обслуживаемого ЛМО ФМБА России – данные Федерального центра информационных технологий экстремальных проблем (ФЦИТЭП) ФМБА России; населения Российской Федерации в целом – данные Московского научного исследовательского онкологического института (МНИОИ) им. П.А.Герцена – филиала НМИЦ радиологии Минздрава России.
Углубленный анализ заболеваемости ЗНО и смертности от них среди работников предприятий и населения, обслуживаемых ЛМО ФМБА России, осуществлялся с использованием данных Отраслевого онкологического регистра ФМБА России.
*Результаты исследования и их анализ.* По результатам проведённого анализа отмечен рост заболеваемости ЗНО как по ЛМО ФМБА России в ЗАТО, во всех ЛМО ФМБА России, так и по Российской Федерации в целом. В 2012–2018 гг. заболеваемость ЗНО (на 100 тыс. населения) составила: в ЗАТО – 412,4 и 526,6 чел. соответственно; во всех ЛМО ФМБА России – 328,4 и 390,1; в Российской Федерации в целом – 367,3 и 425,5 чел. соответственно.
Анализ показателей смертности от ЗНО показал, что во всех ЛМО ФМБА России смертность от ЗНО (на 100 тыс. населения) в данном интервале времени составляла: 149,1 и 167,9 чел. соответственно, что значительно меньше общероссийских

показателей – 201,0 и 200,0 чел. соответственно. Смертность от ЗНО в ЗАТО составила 220,1 и 257,3 чел. соответственно, что превышает показатели как по всем ЛМО ФМБА России, так и по Российской Федерации в целом.

**Ключевые слова:** *заболеваемость, закрытые административно-территориальные образования, злокачественные новообразования, лечебные медицинские организации, население, объекты атомной промышленности, объекты ядерной энергетики, работники радиационно опасных предприятий, смертность, ядерная энергетика*

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***Contact information:***
***Elvira P. Korovkina –*** Cand.Sc.(Biol.); Leading Researcher
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (903)106-05-27
**E-mail:** korovkina@fmbcfmba.ru

***Контактная информация:***
***Коровкина Эльвира Павловна –*** кандидат биологических наук; ведущий научный сотрудник
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, 46
**Тел.:** +7 (903)106-05-27
**E-mail:** korovkina@fmbcfmba.ru

## Introduction

The Federal Medical and Biological Agency (FMBA of Russia) is a unique complex of specialized medical and scientific centers. It allows preserving health and ability to work of people whose professions bear extreme strains or health risks. One of the most important tasks of FMBA of Russia is the fight against oncological diseases and the reduction of overall mortality from malignant neoplasms. A particularly important component of this task is the reduction of premature mortality in working age.

According to the International Agency for Research on Cancer (IARC), the number of cancers is increasing worldwide. This is mainly due to an increase in life expectancy. By 2040, annual number of newly diagnosed cancers is projected to increase from 17.0 million to 27.5 million, an increase of 61.4%. About 40% of cancers can be prevented with structured primary prevention.

On the basis of numerous experimental and epidemiological studies, conclusions were made about the risk factors or etiological factors of tumor appearance. The main cause (90-95%) is lifestyle and environmental factors [1, 2]. These include: smoking and other forms of tobacco consumption; excessive body weight; low physical activity; diet rich in processed meats and meat and poor in fruits and vegetables; alcohol consumption; certain types of viral and bacterial infections; excessive exposure to sunlight; carcinogens in the workplace and in the air [3-5].

Occupational cancers account for 3-5% of the total number. And they can be prevented by taking measures of primary and secondary prevention, as well as by observing occupational hygiene [1, 6].

Monitoring level and dynamics of cancer incidence is necessary to assess the impact of ionizing radiation on the human body. This is the most important for medical professionals, workers at radiation hazardous enterprises, and the population living near nuclear industry and nuclear power facilities.

The carcinogenic effect of ionizing radiation has been proven by a number of epidemiological studies. They have been conducted among those who were exposed medically, in the workplace, during atomic weapons tests, accidents at nuclear power plants and other nuclear facilities, and, of course, during the atomic bombing of Hiroshima and Nagasaki [5-7]. But uncertainty remains in estimates of cancer risk in those who are exposed to long-term occupational sources of ionizing radiation. This points to the need for radiation and epidemiological studies among workers at radiation-hazardous enterprises and population living near nuclear industry and nuclear power facilities [8-11].

**The purpose of the study** is to analyze the oncoepidemiological situation in the vicinity of nuclear industry and nuclear power plants.

*Research Objectives:*

1. Comparative analysis of the dynamics of cancer morbidity and mortality among patients of all medical treatment organizations of FMBA of Russia, among patients of medical organizations of FMBA of Russia in closed administrative-territorial formations of ROSATOM (research sample) and among the population of the Russian Federation as a whole in 2012-2018.

Analysis of the dynamics of morbidity and mortality from cancer by the following age groups: 0-19 years; 20-39 years; 40-59 years; 60-85 years and by nosological forms of the International Classification of Diseases, 10th edition (ICD-10).

**Materials and methods of the study.** The main materials of the study were the data of official medical statistics for 2012 — 2018 on the incidence of malignant neoplasms and mortality from them: contingent of medical organizations of FMBA of Russia from 10 closed administrative-territorial formations — research sample; total contingent served by medical organizations of FMBA of Russia — according to the Federal Center for Information Technologies of Extreme Problems of FMBA of Russia — form № 7 — Information on diseases with malignant neoplasms

An in-depth analysis of the morbidity and mortality from malignant neoplasms among employees of enterprises and population served by medical organizations of FMBA of Russia was performed using data from the Cancer Registry of FMBA of Russia.

To analyze the incidence of malignant neoplasms and mortality from them among workers of radiation hazardous enterprises and population living near nuclear industry and nuclear power facilities, we calculated and analyzed crude intensive (CR) rates of malignant neoplasms morbidity and mortality from them per 100 thousand population.

**Results of the study and their analysis.** According to the results of the statistical analysis, the growth of cancer morbidity in 2012-2018 was observed both for closed administrative-territorial formations (research sample), and for all medical organizations of FMBA of Russia and for the Russian Federation as a whole (Table 1, Fig. 1).

The dynamics of the incidence of malignant neoplasms (per 100 thousand people) among employees and the population of closed administrative-territorial entities (research sample) serviced by medical institutions of FMBA of Russia in 2012-2018 was 412.4-526.5 people. It was 412.4-526.5 people and was higher than the dynamics of indicators for the Russian Federation as a whole (367.3-425.5 people), as well as of indicators for all medical institutions of the Federal Medical and Biological Agency of Russia (328.4-390.1 people).

A higher (4.2%) average annual growth rate of the incidence of cancer of all localizations was registered among the population of 10 closed administrative-territorial entities of FMBA of Russia as compared to that in all medical institutions of FMBA of Russia (2.9%) and in the Russian Federation as a whole (2.7%).

As for age-specific indicators of malignant neoplasms morbidity, as it has been previously noted in our investigations and in the works of other authors, the greatest number of cancer cases was observed in the senior age groups: 40-59 years — 23.3-26.6%; 60-85 years — 72.2-68.3% (Table 2, Fig. 2) [4, 6, 7, 9].

In our studies we also performed a comparative analysis of the dynamics of malignant tumor mortality rates among residents of closed administrative-territorial formations served by the healthcare institutions of the Federal Medical and Biological Agency of Russia, among patients of all healthcare institutions of FMBA of Russia, and cancer mortality rates of the Russian Federation as a whole. The results are presented in Table 3 and Fig. 3.

As can be seen from the data presented in Table 3 and Fig. 3, the dynamics of cancer mortality (per 100,000 population) among patients of all medical institutions of the Federal Medical and Biological Agency of Russia in 2012-2018 was 149.1-167.9, which is significantly lower than the all-Russian rates: 201.0-200.0. This can be explained by earlier detection of diseases and the quality of medical care in the medical institutions of the Federal Medical and Biological Agency of Russia. The mortality rate from cancer (per 100 000 of population) among the residents of closed administrative-territorial formations over the period of time amounted to 220,1-257,3 persons. This exceeds the mortality rates both among patients of all medical institutions of FMBA of Russia and in the Russian Federation as a whole.

It should be emphasized that malignant neoplasms are heterogeneous diseases and both environmental and hereditary factors are involved in their development [3-5].

Our previous works have described the influence of lifestyle factors (smoking, alcohol), socioeconomic factors

*Таблица 1/Table No. 1*

**Динамика заболеваемости ЗНО (на 100 тыс. населения) пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и населения Российской Федерации в целом в 2012–2018 гг., чел.**

The dynamics of cancer incidence (per 100,000 people) among patients of closed administrative territorial entities' medical facilities of FMBA of Russia; patients of all medical facilities of FMBA of Russia and population of the Russian Federation as a whole for 2012-2018, people

| Контингент Contingent | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | Среднегодовой темп прироста, % Compound annual growth rate, % |
|---|---|---|---|---|---|---|---|---|
| Пациенты ЛМО ФМБА России в ЗАТО Patients of closed administrative territorial entities' medical facilities of FMBA of Russia | 412,4 | 436,3 | 486,4 | 458,1 | 450,2 | 496,8 | 526,5 | 4,15 |
| Пациенты всех ЛМО ФМБА России Patients of all medical facilities of FMBA of Russia | 328,4 | 325,0 | 355,5 | 345,8 | 359,6 | 375,1 | 390,1 | 2,91 |
| Население Российской Федерации в целом Population of the Russian Federation as a whole | 367,3 | 373,4 | 388 | 402,6 | 408,6 | 420,3 | 425,5 | 2,7 |

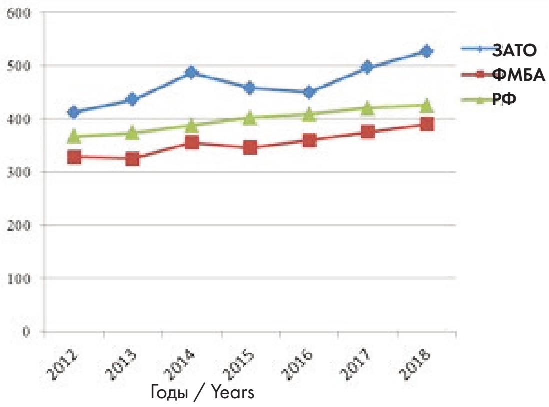


**Рис. 1.** Динамика заболеваемости ЗНО (на 100 тыс. населения) пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и населения Российской Федерации в целом в 2012–2018 гг., чел.

**Fig. 1.** Dynamics of the incidence of cancer (per 100 thousand population) of patients of the LMO of the FMBA of Russia in the closed city; patients of all LMO FMBA of Russia and the population of the Russian Federation as a whole in 2012–2018, people

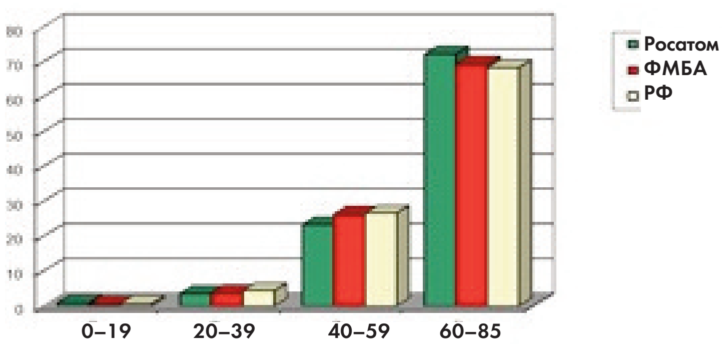


**Рис. 2.** Распределение по возрастным группам заболевших ЗНО среди пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и населения Российской Федерации в целом в 2018 г., %

**Fig. 2.** Distribution by age groups of cancer patients among patients of the LMO FMBA of Russia in the closed city; patients of all LMO FMBA of Russia and the population of the Russian Federation as a whole in 2018,%

*Таблица 2 /Table No. 2*

**Распределение по возрастным группам заболевших ЗНО среди пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и населения Российской Федерации в целом в 2018 г.**

Incidence of cancers by age group among patients of closed territorial entities' medical facilities of FMBA of Russia, patients of all medical facilities of FMBA of Russia and population of the Russian Federation as a whole in 2018

| Контингент<br>Contingent | Число заболевших ЗНО, чел., всего<br>Number of cancer patients, people, total | Заболеваемость ЗНО по возрастным группам, чел./%<br>Incidence of cancers by age group, persons/% | | | |
|---|---|---|---|---|---|
| | | 0–19 лет<br>0-19 y.o. | 20–39 лет<br>20-39 y.o. | 40–59 лет<br>40-59 y.o. | 60–85 лет<br>60-85 y.o. |
| Пациенты ЛМО ФМБА России в ЗАТО<br>Patients of closed territorial entities' medical facilities of FMBA of Russia | 3777 | 33/0,9 | 135/3,6 | 881/23,3 | 2728/72,2 |
| Пациенты всех ЛМО ФМБА России<br>Patients of all medical facilities of FMBA of Russia | 10243 | 50/0,5 | 394/3,8 | 2699/26,3 | 7100/69,3 |
| Население Российской Федерации в целом<br>Population of the Russian Federation as a whole | 624709 | 4389/0,7 | 27331/4,4 | 166229/26,6 | 426760/68,3 |

*Таблица 3/Table No. 3*

**Динамика смертности от ЗНО (на 100 тыс. населения) среди пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и среди населения Российской Федерации в целом в 2012–2018 гг., чел.**

The dynamics of mortality from cancer (per 100,000 people) among patients of closed administrative territorial entities' medical facilities of FMBA of Russia; patients of all medical facilities of FMBA of Russia and population of the Russian Federation as a whole for 2012-2018, people

| Контингент<br>Contingent | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | Среднегодовой темп прироста,%<br>Compound annual growth rate, % |
|---|---|---|---|---|---|---|---|---|
| Пациенты ЛМО ФМБА России в ЗАТО<br>Patients of closed territorial entities' medical facilities of FMBA of Russia | 220,1 | 219,1 | 232,8 | 226,1 | 245,6 | 241,9 | 257,3 | 2,6 |
| Пациенты всех ЛМО ФМБА России<br>Patients of all medical facilities of FMBA of Russia | 149,1 | 143,0 | 154,5 | 154,0 | 168,3 | 172,6 | 167,9 | 2,0 |
| Население Российской Федерации в целом<br>Population of the Russian Federation as a whole | 201,0 | 201,1 | 199,5 | 202,5 | 201,6 | 197,9 | 200,0 | 0,1 |

and environmental factors, including occupational exposures on the occurrence of malignant diseases and mortality from them — both on patients of medical institutions of FMBA of Russia and on the population of the Russian Federation as a whole [12].

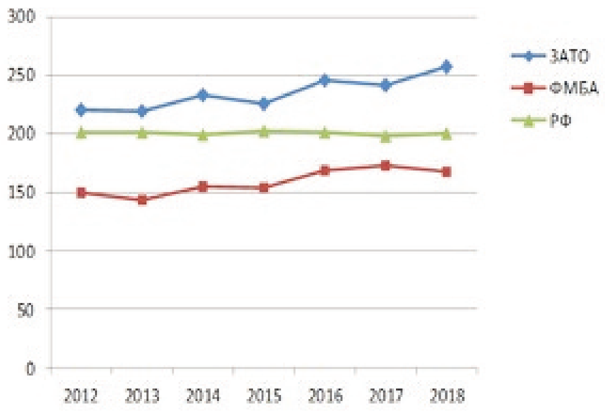


**Рис. 3.** Динамика смертности от ЗНО (на 100 тыс. населения) пациентов ЛМО ФМБА России в ЗАТО; пациентов всех ЛМО ФМБА России и населения Российской Федерации в целом в 2012–2018 гг., чел.
**Fig. 3.** Dynamics of mortality from malignant neoplasms in patients at medical facilities of the ZATO, FMBA and the RF for 2012-2018

In 2018, in the structure of mortality from malignant neoplasms (ICD-10) in medical institutions of FMBA of Russia, the largest share of tumors were of trachea, bronchi, lung (13.7%), stomach (10.3%), colon (9.1%), breast (8.7%), rectum, rectosigmoid junction, anus (6.3%), prostate (5.4%), lymphoid and hematopoietic tissue (5.3%). In the Russian Federation as a whole in 2018 the structure of population mortality from cancer was similar [13].

**Conclusion**

A study of the morbidity rates for malignant neoplasms of the employees of enterprises, organizations and attached population served by medical institutions of FMBA of Russia showed that they slightly differ from the all-Russian rates: the morbidity rate of this population is lower than in Russia as a whole. The ratio of morbidity in closed administrative-territorial entities/institutions of the Federal Medical and Biological Agency of Russia as a whole is 1.3; FMBA of Russia/Russian Federation as a whole is 0.9.

The dynamics of cancer mortality in the FMBA health care institutions in the studied time interval was 149.1-167.9, which is significantly less than the all-Russian figures of 201.0-200.0.

An analysis of the cancer mortality rates of employees of enterprises, organizations and attached population served by medical institutions of FMBA of Russia also revealed positive trends: the level of overall mortality (the number of deaths per 100 thousand people) among the contingent served by institutions of FMBA of Russia was significantly lower than in Russia as a whole — the ratio for mortality of FMBA of Russia / Russian Federation as a whole — 0.47.

As for age-specific indicators of cancer morbidity in the contingents under study, we can note that, as in the Russian Federation as a whole, the greatest number of malignant neoplasms was observed in the older age groups: 40-59 years: 23.3-26.6%; 60-85 years: 72.2-68.3%.

Thus, the incidence of malignant neoplasms grew in all study groups at approximately the same rate — the growth rate was statistically significantly different from 0 and was about 3% per year.

Mortality rates from malignant neoplasms were also within the described trends.

The greatest attention is attracted by the "leadership" of the population of closed administrative-territorial formations in terms of morbidity and mortality in comparison with all medical institutions of FMBA of Russia and the population of the Russian Federation as a whole. We would like to warn our readers against making radiophobic conclusions: there are no radiation risks there! We mentioned this when describing the contribution of the radiation factor to the carcinogenic situation [12]. It is the population of closed administrative-territorial formations, as a community unique in its mental, national, professional and qualification characteristics, that is the main point of application of FMBA's efforts to improve health, to prevent and to rehabilitate diseases. It is by improving the quality of life and saving active professional longevity that the average age of the population there is higher than the average age of Russia as a whole, and 72.2% of malignant neoplasms occur in the age group of 60-85 years.

The conducted studies testify to the fact that further cancer control as an important strategic direction in the activity of the Federal Medical and Biological Agency should be based on the understanding of the complex carcinogenic environment of the industrial and domestic sphere as an integral danger of damage to human health. This dictates the need to improve the practice of hygienic regulation in the conditions of normal operation of radiation hazardous facilities, taking into account domestic experience and international norms and rules. It also requires introduction of new effective forms of organization and management of sanitary and epidemiological well-being.

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**Original article**



# RISK OF DEATH FROM HYPERTENSION AMONG CHERNOBYL ACCIDENT LIQUIDATORS — NUCLEAR INDUSTRY WORKERS

A.R.Tukov[1], I.L.Shafranskiy[1], O.N.Prokhorova[1], M.V.Kalinina[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** *The aim of the study* was to assess the radiation risk of death from hypertension in liquidators of the Chernobyl nuclear power plant accident consequences — workers of the nuclear industry — using doses from various types of irradiation.
*Materials and methods of the study.* The study was conducted using data from the Industry Register of Persons exposed to radiation as a result of the Chernobyl accident — workers of the nuclear power industry. Information on 12659 liquidators (all male) was included in the analysis. 1327 of them got occupational radiation doses. Crude relative risks of death from hypertension were estimated for five dose groups using internal controls. Based on the stratified data file, a Poisson regression procedure was performed using the AMFIT module of Epicure program and the excess relative risk of death from hypertension was calculated and the nature of the dose-dependent excess relative mortality was investigated.
*Results of the study and their analysis.* Direct estimates of radiogenic risk of death from hypertension were obtained. No increase in mortality from hypertensive disease per unit dose was found for both the doses received during the liquidation of the Chernobyl accident consequences and for the total doses. The results of the study can be used in the development of radiation safety regulations for persons working with sources of ionizing radiation.

**Key words:** *AMFIT, Chernobyl accident, EPICURE, hypertension, industry register, liquidators, nuclear industry workers, radiation, relative risk, risk of death, Rosatom State Corporation, study period*

**Conflict of interest.** The authors declare no conflict of interest

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**Оригинальная статья**



# РИСК СМЕРТИ ОТ ГИПЕРТОНИЧЕСКОЙ БОЛЕЗНИ У ЛИКВИДАТОРОВ ПОСЛЕДСТВИЙ АВАРИИ НА ЧЕРНОБЫЛЬСКОЙ АЭС – РАБОТНИКОВ АТОМНОЙ ПРОМЫШЛЕННОСТИ

А.Р.Туков[1], И.Л.Шафранский[1], О.Н.Прохорова[1], М.В.Калинина[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** *Цель исследования* – оценка радиационного риска смерти от гипертонической болезни у ликвидаторов последствий аварии на Чернобыльской АЭС (ЧАЭС) – работников атомной промышленности с использованием доз от различных видов облучения.
*Материалы и методы исследования.* Исследование проводилось с использованием данных Отраслевого регистра лиц, подвергшихся воздействию радиации в результате аварии на ЧАЭС – работников атомной промышленности.В анализ была включена информация о 12659 ликвидаторах (все – мужчины), 1327 из которых имели дозу профессионального облучения. Оценены грубые относительные риски смерти от гипертонической болезни для пяти дозовых групп с использованием внутреннего контроля. На основе файла стратифицированных данных проведена процедура Пуассоновской регрессии с использованием модуля AMFIT программы Epicure и рассчитана величина избыточного относительного риска смерти от гипертонической болезни, а также исследован характер дозовой зависимости избыточной относительной смертности.
*Результаты исследованияи их анализ.* Получены прямые оценки радиогенного риска смерти от гипертонической болезни. Не обнаружено увеличения смертности от гипертонической болезни на единицу дозы как для дозовых нагрузок, полученных при ликвидации последствий аварии на ЧАЭС, так и для суммарных доз. Результаты исследования могут быть использованы при разработке регламентов радиационной безопасности лиц, работающих с источниками ионизирующего излучения.

**Ключевые слова:** *AMFIT, EPICURE, авария на Чернобыльской АЭС, гипертоническая болезнь, Госкорпорация «Росатом», ликвидаторы – работники атомной промышленности, относительный риск, отраслевой регистр, период исследования, радиация, риск смерти*

**Конфликт интересов.** Авторы статьи подтверждают отсутствие конфликта интересов

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**_Contact information:_**
**_Aleksandr R. Tukov_** – Cand. Sc. (Med.); Head of the Laboratory
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (499) 190-94-81
**E-mail:** atukov40@mail.ru

**_Контактная информация:_**
**_Туков Александр Романович_** – кандидат медицинских наук; заведующий лабораторией
**Адрес:** Россия, 123098, Москва, ул. Живописная, 46
**Тел.:** +7 (499) 190-94-81
**E-mail:** atukov40@mail.ru

Recently, there has been an interest in the impact of ionizing radiation on morbidity and mortality from non-oncologic somatic pathology. This is due to the emergence of a large body of clinical evidence of the damaging effects of radiation on the cardiovascular system.

At the same time, on the basis of data on survivors of the atomic bombing in Japan (LSS), it is shown that in the analysis of cardiovascular mortality, no statistically significant risk value was presented for any dose stratum of the total dose category relative to the control population (less than 0.2 Gy). And even the addition of additional corrective factors did not change this result [1]. Estimates of excess relative risk per Gy (ERR/Gy) corresponded to the level not exceeding the risk.

As for Russian liquidators of the Chernobyl NPP (ChNPP) accident consequences, there is a point of view that low dependence of population risks of somatic diseases on the value of radiation dose received in 30-km (30-km) ChNPP zone is connected with erroneous estimation of radiation exposure dose received by liquidators, and also with functional instability of diagnostic indicators change in time [2, 3]. According to data of Russian State Medical and Dosimetric Registry, excess relative risk of cardiovascular diseases (ERR/Zv) has a value of 0.4 — significantly different from zero, and of mortality from cardiovascular diseases is 0.2 — not significantly [4].

According to the data of Ukrainian researchers, in spite of the fact that clinical characteristics of the functional state of cardiovascular system and concomitant diseases in the liquidators were almost similar to those observed in the control group, the beginning of hypertensive disease in this contingent came earlier — at 55.9 years — against 59.8 years in the control group [5]. It was also shown that in the persons who took part in the liquidation of the Chernobyl accident at the age of 40 and older at the time of the accident, irradiation in low doses caused the development of hypertensive disease. The mortality rate in these persons with higher radiation doses was significantly higher ($p<0.05$) than in persons with lower radiation doses. The main causes of mortality from circulatory system diseases in the studied cohorts were cerebro-vascular diseases, arterial hypertension, diseases of arteries, arterioles and capillaries [6, 7].

Also of interest are estimates from national registries of nuclear power workers and uranium ore miners (Germany). According to NRRW (England) and their German colleagues, estimates of ERR/Gy for cardiovascular mortality do not differ significantly from zero, which also corresponds to the data of T.V. Azizova on the cohort of "Mayak" Industrial Association workers [8-12].

M.P.Little presented the results of the IARC/HS estimates on the LSS cohort data for cardiovascular disease mortality, which were 0.17 (0.08-0.26) — [13]. An analysis of IARC data from a study of nuclear-cycle worker mortality in 15 countries yielded lower estimates for morbidity in selected nosologies (coronary heart disease, hypertension, heart attacks, embolisms) that were generally close to zero. His analysis of morbidity data of Chernobyl accident liquidators yielded the following results for ERR/Zv: hypertension, 0.26; coronary heart disease, 0.41; other cardiovascular pathologies, 0.26. Except for the latter, the first 2 coefficients were significantly different from zero. In the work on meta-analysis of data presented by researchers from many countries, the ERR/Zv value for death from coronary heart disease was 0.10 [14].

Great work on the analysis of mortality data for employees of nuclear-cycle enterprises was carried out by E. Cardis and co-authors [15]. The risk of death from all diseases, excluding cancer, was 0.24 per 1 Sv; for cardiovascular diseases it was 0.09 per 1 Sv. For both coefficients, the confidence interval includes zero.

Unfortunately, the studies presented above were made using data on doses of a single type of exposure and therefore their results cannot be reliable. In this connection, it is relevant to carry out studies to assess the risk of radiation-induced diseases or death from them using total doses from different types of irradiation.

**The aim of the study** was to assess the radiation risk of death from hypertensive disease in the liquidators of the Chernobyl accident consequences — workers of the nuclear industry — using doses from various types of radiation.

**Materials and research methods.** The data on employees of enterprises and organizations of the State Corporation "Rosatom" who participated in liquidation of consequences of the Chernobyl accident were used in the work. The analysis included information on 12,659 liquidators (male) registered in the Industry Register of the persons exposed to the Chernobyl NPP accident and having data on verified external radiation doses. The average age of the liquidators at the time of participation in the liquidation of the Chernobyl accident consequences was 36.6 years; 80% of the liquidators were in the 30-40 age group.

At present, due to the fact that none of the medical dosimetric registers meet the requirements of Radiation Safety Norms of 1999 — availability of total radiation dose to calculate radiation risk — there is no possibility to perform correct studies on risk assessment for radiation-induced diseases at low doses on existing registers both in our country and abroad.

Rosenergoatom OJSC provided the State Research Center — Federal Medical Biophysical Center named after A.I. Burnazyan of the Federal Medical and Biological Agency (FMBA of Russia) with the data on occupational radiation doses to main production workers at 10 NPPs who were under individual dosimetry control and who participated in the liquidation of the Chernobyl accident consequences. Data on occupational radiation doses of Balakovo, Beloyarsk, Bilibino, Kalinin, Kola, Kursk, Leningrad, Novovoronezh, Rostov and Smolensk NPP workers are included in the development.

In addition, data on occupational radiation doses to employees of enterprises and organizations of ROSATOM were obtained from healthcare institutions of the Federal Medical and Biological Agency of Russia.

Occupational exposure doses were presented by years of their work with radioactive substances and ionizing radiation sources, starting from the first year of work and ending in 2015. Cumulative doses were also calculated, which were linked to the accident liquidators included in the Industry Register.

The data on external radiation doses among the liquidators during their stay in the 30-km ChNPP zone are presented in Table 1.

Table 2 shows some characteristics of the generalized database of the Register by 5 dose groups — both by doses at the Chernobyl NPP and by total doses. The groups were formed from an approximately equal number of persons and taking into account the radiation doses received.

In the structure of total doses received by the liquidators of the Chernobyl accident consequences while working in the 30-km zone and during their professional activities, 48% were doses up to 100 mSv; 6% of the liquidators had doses higher than 500 mSv.

Table 3 provides information on the average, minimum and maximum external radiation doses received by the liquidators at various work sites.

The study calculated the 95% confidence interval of the indicators.

The applied statistical software package EPICURE (AMFIT module), widely used in modern radiation and epidemiological practice, was used for risk assessments based on age-, dose-, and other groups of data [16]. The methodology of radiation risk assessment is implemented in this package. The AMFIT program is a recognized standard for radiation and epidemiological studies. Radiation risk assessments among the personnel of ROSATOM enterprises and organizations were performed using this program. The model of excess relative risk in general form is presented by formula 1:

$$\lambda_d = \lambda_0 \times (1+\beta \times d) \qquad (1)$$

where $\lambda_d$ – is the incidence rate; $\lambda_0$ – is the spontaneous incidence rate; $\beta$ – is the excess relative risk; *d* is the radiation dose.

*Таблица 1/Table No. 1*

**Дозы внешнего облучения у ликвидаторов (мужчины и женщины) последствий аварии на ЧАЭС**

Provision of Liquidators (Men and Women) of the Consequences of the Chernobyl Accident with Data on External Exposure Doses

| Годы въезда в 30-км зону Years entrance to the 30-km zone | Число ликвидаторов, чел. Amount liquidators, people | В том числе с дозой, чел./% Of these there is a dose, people/% | Среднее значение дозы, мЗв Average value, mSv |
|---|---|---|---|
| 1986–1990 | 18450 | 12698/68,8 | 55,3 |
| 1986 | 10790 | 7276/67,4 | 74,8 |
| 1987 | 4738 | 3365/71,0 | 33,1 |
| 1988 | 1868 | 1389/74, 4 | 25,7 |
| 1989 | 798 | 571/71,6 | 16,8 |
| 1990 | 266 | 97/36,5 | 11,9 |

The likelihood function is constructed based on the assumption that the number of cases is an independent Poisson random variable.

**The results of the study and their analysis.**

To calculate the relative radiation risk of mortality from hypertension among the liquidators of the Chernobyl accident consequences using the AMFIT program the data were divided into 5 dose groups obtained during the liquidation of the Chernobyl accident and the total dose (Tables 4, 5).

Formula 2 was used to estimate the reliability of the relative radiation risk of mortality:

$$\log RR\ (SE) = \sqrt{(1/r1 + 1/r2 - 1/N1 - 1/N2)} \qquad (2)$$

where *r1, r2* — number of cases in the control and current strata; *N1, N2* — number of person-years in the control and current strata.

Due to the small values of relative risk, all values of point risks do not reliably exceed 1, which makes it impossible to make parallel comparisons. At the same time, according to the data in Tables 4 and 5, the relative risk values for mortality from hypertension have some tendency to increase inversely.

The results of radiation risk assessment using the AMFIT program for different dose loads are given in Table 6. The excess relative risk was not detected both in the case of taking into account only doses received in Chernobyl, and in the case of total doses.

The case of a uniform expansion of the dose range — the addition of occupational exposure doses in each stratum — leads to a shift of the regression line of the risk curve to the right along the axis of dose values. In the empirical control problem, this automatically leads to a reduction in excess risk. In the case of unequal addition of dose loads by strata — an increase in doses due to occupational exposure only for 1327 people out of 12659 — the "risk" response can be paradoxical.

**Discussion**

As noted by a number of authors, there are different approaches to explaining the pathogenesis of the development of cardiovascular diseases in the long-term period [17]. Some authors consider the role of chronic emotional stress exclusively. Others argue that the damaging effect of ionizing radiation does not depend on human consciousness and in case of uniform irradiation of the organism is manifested at the cellular-molecular level in all organs and tissues without exception [18]. Apparently, the prognostic significance in the development of cardiovascular diseases in liquidators of the concept of disintegrative syndrome as a nonspecific radiation syndrome in contrast to acute or chronic radiation disease considered as a specific radiation syndrome is a priority.

At present, total radiation doses received by workers both at Chernobyl and during their main job, as well as medical and natural doses of exposure, are of particular relevance

*Таблица 2 /Table No. 2*

**Дозы внешнего облучения у ликвидаторов (мужчины) последствий аварии на ЧАЭС**

Provision of Liquidators (Men) of the Consequences of the Chernobyl Accident with Data on External Exposure Doses

| Дозовая группа – ЧАЭС Dose group – ChNPP | Число ликвидаторов, чел. Number of liquidators, people | Средняя доза, мЗв Average dose, mSv | Дозовая группа – проф. Dose group – professional | Число ликвидаторов, чел. Number of liquidators, people | Средняя доза, мЗв Average dose, mSv |
|---|---|---|---|---|---|
| 0,1–4,9 | 2864 | 2,23 | 0,1–5,9 | 2922 | 2,6 |
| 5,0–12,9 | 2237 | 7,95 | 6,0–16,7 | 2222 | 10,3 |
| 13,0–35,1 | 2490 | 21,70 | 17,0–48,8 | 2468 | 30,4 |
| 36,0–98,8 | 2516 | 62,30 | 49,0–120,5 | 2482 | 80,3 |
| 99,0–1478,5 | 2552 | 181,80 | 121–1985,6 | 2565 | 228,4 |

*Таблица 3 /Table No. 3*

**Распределение доз облучения у ликвидаторов в зависимости от места их работы, мЗв**

Distribution of Radiation Doses among Liquidators Depending on the Place of Work, mSv

| Место получения дозы<br>A place receiving dose | Средняя доза<br>Average dose | Минимальная доза<br>Minimum dose | Максимальная доза<br>Maximum dose |
|---|---|---|---|
| ЧАЭС/ChNPP | 55,2 | 0,1 | 1478,50 |
| Предприятия Госкорпорации «Росатом»<br>Enterprises of the State Corporation "Rosatom" | 180,8 | 0,1 | 1832,40 |
| Взвешенная сумма доз<br>Weighted sum of doses | 70,5 | 0,2 | 1847,72 |

*Таблица 4 /Table No. 4*

**Значения стратифицированных показателей смертности от гипертонической болезни (на 1000) и ОР для ликвидаторов (мужчины) последствий аварии на ЧАЭС – работников предприятий и организаций Госкорпорации «Росатом» (дозы ЧАЭС)**

Values of Stratified Mortality Rates from Essential Hypertension (per 1000) and RR for Liquidators of the Consequences of the Chernobyl Accident, Men - Employees of Enterprises and Organizations of the State Corporation "Rosatom" (Doses of the Chernobyl NPP)

| Средняя доза, мЗв<br>Average dose, mSv | Смертность (на 1000)<br>(МКБ 10: I10-I15.9)<br>Mortality (per 1000)<br>(ICD 10: I10-I15.9) | ОР/RR |
|---|---|---|
| 2,23 | 1,21 | 1,00 |
| 7,95 | 0,84 | 0,70 |
| 21,70 | 1,32 | 1,09 |
| 62,30 | 1,11 | 0,92 |
| 181,00 | 0,89 | 0,74 |

*Таблица 5 /Table No. 5*

**Значения стратифицированных показателей смертности от гипертонической болезни (на 1000) и ОР для ликвидаторов (мужчины) последствий аварии на ЧАЭС –работников предприятий и организаций Госкорпорации «Росатом» (дозы ЧАЭС + профессиональные)**

Values ofStratified Mortality Rates from Hypertension (per 1000) and OR for Liquidators (Men) of the Consequences of the Chernobyl Accident - Employees of Enterprises and Organizations of the State Atomic Energy Corporation Rosatom (Doses of ChNPP + Professional)

| Средняя доза, мЗв<br>Average dose, mSv | Смертность (на 1000)<br>(МКБ 10: I10-I15.9)<br>Mortality (per 1000)<br>(ICD 10: I10-I15.9) | ОР<br>RR |
|---|---|---|
| 2,6 | 1,24 | 1,00 |
| 10,3 | 1,04 | 0,84 |
| 30,4 | 1,25 | 1,00 |
| 80,3 | 0,97 | 0,78 |
| 228,4 | 0,91 | 0,74 |

*Таблица 6 /Table No. 6*

**Оценка радиационных рисков смертности от гипертонической болезни с использованием программы AMFIT для различных дозовых нагрузок, ИОР/Зв**

Estimate of the radiation risks of mortality from hypertension using the AMFIT program for various dose loads (ERR/Sv)

| Тип дозы<br>Dose type | ИОР/Зв<br>ERR/Sv | ДИ (95%)<br>CI (95%) |
|---|---|---|
| ЧАЭС доза /Chernobyl dose | -0,28 | -2,3–2,0 |
| Суммарно с профдозой<br>In total with the professional dose | -0,31 | -1,37–1,52 |

in risk analysis. The available results of worldwide dosimetry studies also indicate that exposure to the A-bomb cannot be reliably assessed unless medical X-ray doses are fully included in these long-term assessments [19].

For the first time we obtained the results on the assessment of the risk of exposure from the combined dose of two types of exposure. However, the process of collecting complete information is currently in its infancy, and it will be shown in the future how much consideration of medical and natural doses is needed in population risk analysis.

The liquidators in the distant terms of observation after the liquidation of the accident consequences need medical care aimed at the prevention and treatment of such most common and socially significant diseases as cardiovascular diseases.

The results we obtained can be used in the development of radiation safety regulations.

The uniqueness of the liquidator cohort for obtaining direct estimates of the risk of distant effects of radiation exposure at low doses indicates the need for surveillance of this population. Further research involves increasing the statistical power of the analysis by extending the follow-up period, as well as working to reduce uncertainties in dose estimates and to improve the completeness and quality of epidemiological data.

**Conclusion**

1. Evaluation of the calculation of the risk of death from hypertension using data on the doses of different types of exposure showed no difference in the results obtained.

2. No increase in the risk of death from hypertension was noted with increasing dose.

3. To reliably assess the risk of radiation-induced diseases or death from them it is necessary to create a medical and dosimetric register of nuclear industry workers with data on the doses of all types of exposure — occupational, accidental, medical, natural.

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# RADIATION RISKS OF HELICOPTER PERSONNEL RESPONDING TO THE CHERNOBYL ACCIDENT: EARLY AND LONG-TERM HEALTH DISORDERS

I.B.Ushakov [1], V.P.Fedorov [2]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation
[2] Voronezh State Institute of Physical Culture, Voronezh, Russian Federation

**Abstract.** *The objectives of the study* were to analyze the radiation doses received by helicopter crew members during the work above the emergency unit and the effectiveness of some radioprotective means; to determine the most radiosensitive systems of the body, their condition in the early and distant terms after the accident and the causes of disqualification of flight personnel.
*Materials and research methods.* The first stage of the work was performed directly in the zone of helicopter aviation flight over the Chernobyl NPP emergency power unit. We determined radiation doses received by flight personnel, their dependence on the type of helicopter and pilot's workplace. Also we evaluated the dependence of exposure dose on the radio-protective means used and the primary reaction of pilots to radiation exposure. The second stage of the work was performed on the basis of the Central Research Aviation Hospital and the State Research Test Institute of Military Medicine of the Russian Ministry of Defense. At this stage the results of laboratory, clinical and psychological examination of the pilots who performed the tasks of liquidation of the Chernobyl accident effects in 1986 - 1987 and received regulated radiation doses were assessed. The corresponding medical documents (expert decisions of medical and aviation committees, results of medical follow-up) were studied for the period from 1986 till 2000, i.e. till the time when almost all helicopter liquidators were disqualified for health reasons or discharged due to senior service.
*Results of the study and their analysis.* The radiation doses received by the helicopter crew members during the execution of the assigned tasks over the emergency unit and the efficiency of some radio-protective means were analyzed. The most radiosensitive body systems, their condition in the early and distant terms after the accident and the diseases leading to the disqualification of flight personnel were determined.

***Key words:*** *accident consequences elimination, Chernobyl accident, distant health disorders, early health disorders, helicopter pilots, human exposure to low doses of radiation, ionizing radiationradiation risks*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***


# РАДИАЦИОННЫЕ РИСКИ ВЕРТОЛЁТЧИКОВ ПРИ ЛИКВИДАЦИИ ПОСЛЕДСТВИЙ АВАРИИ НА ЧЕРНОБЫЛЬСКОЙ АЭС: РАННИЕ И ОТДАЛЕННЫЕ НАРУШЕНИЯ ЗДОРОВЬЯ

И.Б.Ушаков[1], В.П.Фёдоров[2]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия
[2] ФГБОУ ВО «Воронежский государственный институт физической культуры», Воронеж, Россия

**Резюме.** *Цели исследования* – проанализировать дозы облучения, полученные членами экипажей вертолетов во время работы над аварийном блоком, и эффективность некоторых радиозащитных средств; определить наиболее радиочувствительные системы организма, их состояние в ранние и отдаленные сроки после аварии и причины дисквалификации летного состава.
*Материалы и методы исследования.* Первый этап работы был выполнен непосредственно в зоне полета вертолетной авиации над аварийным энергоблоком Чернобыльской АЭС. При этом определяли дозы радиационного воздействия, полученные летным составом, их зависимость от типа вертолета и рабочего места летчика, а также оценивали зависимость дозы облучения от применяемых радиозащитных средств и первичную реакцию летчиков на радиационное воздействие. Второй этап работы выполняли на базе Центрального научно-исследовательского авиационного госпиталя (ЦНИАГ) и Государственного научно-исследовательского испытательного института военной медицины Минобороны России. На данном этапе оценивали результаты лабораторных, клинических и психологических обследований летчиков, выполнявших задачи по ликвидации последствий аварии на ЧАЭС в 1986–1987 гг. и получивших регламентированные дозы облучения; изучали соответствующие медицинские документы (экспертные решения врачебно-летной комиссии, результаты диспансерного наблюдения) за период с 1986 по 2000 гг., т.е. до того срока, когда практически все вертолетчики-ликвидаторы были дисквалифицированы по состоянию здоровья или демобилизованы по выслуге лет.
*Результаты исследования и их анализ.* Проанализированы дозы облучения, полученные членами экипажей вертолетов во время выполнения поставленных задач над аварийном блоком и эффективность некоторых радиозащитных средств. Установлены наиболее радиочувствительные системы организма, их состояние в ранние и отдаленные сроки после аварии и заболевания, приводящее к дисквалификации летного состава

**Ключевые слова:** авария на Чернобыльской АЭС, воздействие малых доз радиации на человека, ионизирующее излучение, лётчики вертолетной авиации, ликвидация последствий аварии, отдаленные нарушения здоровья, радиационные риски, ранние нарушения здоровья

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***Contact information:***
***Igor B. Ushakov –*** Dr. Sc. (Med.), Prof., Acad. of the RAS; General Practitioner, Department of Physical and Rehabilitation Medicine
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7(812)702-63-45
**E-mail:** ibushakov@gmail.com

***Контактная информация:***
***Ушаков Игорь Борисович –*** доктор медицинских наук, академик РАН, профессор; главный научный сотрудник отдела экспериментальной радиобиологии радиационной медицины
**Адрес:** Россия, 123098, Москва, ул. Живописная, 46
**Тел.:** +7(812) 702-63-45
**E-mail:** ibushakov@gmail.com

Thirty-five years have passed since that tragic day when the worst radiation accident in the history of mankind occurred. For the first time military aviation was widely used to eliminate its consequences. Its personnel were exposed to radiation. Already on the second day the crews of the arriving helicopters began to work above the destroyed reactor. Flights to the zone of Unit 4 of the Chernobyl Nuclear Power Plant (ChNPP) were performed for the purpose of dropping heat-removal and filtering materials and measuring radiation levels, including in "hover mode". Aviation was also involved in aerial surveying, reconnaissance of the area, decontamination of the territory and firefighting. More than 1 thousand members of military helicopter aviation crews took part in rescue operations in the early (up to 15 days after the accident) and intermediate (up to 2 months after the accident) periods. The external gamma and beta radiation doses to the liquidators were 0.05-0.5 Gy. The duration of stay in the zone with increased level of contamination by nuclear fission products was up to 10 days [1-4].

Along with the above mentioned, the accident at the Chernobyl NPP set a task for the military medicine to evaluate the nearest and distant consequences of low-dose irradiation. And also to develop on this basis a complex of organizational medical measures, contributing to maintaining the required level of health and working capacity of servicemen during their work in the radioactively contaminated area. This was mainly related to the peculiarity of the action of low radiation doses, namely to the occurrence of various diseases, including psychosomatic ones, among the liquidators [5-9]. Epidemiological studies have shown that during the first 5 years after exposure an annual increase of morbidity was observed in the liquidators. In 10 years 38% of 1986 liquidators had various chronic diseases. And the morbidity occurred in 50% of those surveyed who received a radiation dose of more than 25 cGy. It was shown that 70% of liquidators had the main disease for the first time after liquidation of the Chernobyl NPP accident consequences. And within 17 years the average number of diagnoses per one liquidator increased from 1.4 to 7.2 [10]. At the same time the number of neuropsychiatric diseases in the liquidators was more than 5 times higher than in the control group [11, 12]. No precise information on the pathogenesis of diseases and on the state of the most critical systems of the organism of liquidators exposed to undetermined doses has been obtained. Some researchers consider certain complaints of liquidators as a manifestation of the intention to receive additional benefits or as radiophobia [6]. In this regard, it is necessary to continue such studies, excluding the influence of concomitant factors of non-radiation nature and manifestations of radiophobia.

**The objectives of the study** are to analyze the radiation doses received by helicopter crew members during the work above the 4th unit of the reactor and the effectiveness of some radioprotective equipment; to determine the most radiosensitive body systems, their condition in the early and distant periods after the accident and the causes of disqualification of flight personnel.

**Materials and research methods.** The first stage of the work was performed directly in the zone of helicopter aviation flight over the Chernobyl NPP emergency power unit. At the same time we determined radiation doses received by the flight personnel, their dependence on the type of helicopter and the pilot's workplace. We also evaluated the dependence of exposure doses on the radio-protection equipment used and the primary reaction of pilots to radiation exposure. The second stage of the work was performed on the basis of the Central Research Aviation Hospital and the State Research Test Institute of Military Medicine of the Russian Ministry of Defense. At this stage the results of laboratory, clinical and psychological examination of the pilots who performed the tasks of liquidation of the Chernobyl accident effects in 1986-1987 and received regulated radiation doses were assessed. The corresponding medical documentation (expert decisions of medical and flight committees, results of medical follow-up) was studied for the period from 1986 till 2000, i.e. till the time when almost all helicopter liquidators were disqualified for health reasons or discharged due to senior service. The methodology of the study of the health status of flight personnel from the moment of exposure to radiation until discharge from the Armed Forces (AF) was presented by us earlier [1] in sufficient detail.

**The results of the study and their analysis.** An assessment of the spatial and time parameters of the dose field directly over the reactor showed a significant radiation hazard when flying over the emergency unit. Therefore, for crews operating in emergency situations for 2-5 days, flying over the reactor was considered to be a factor determining the dose load [1]. In indirect assessment of dose loads on flight crews, the nature of the route, altitude, date, and time of day of flight over the emergency zone for each crew were taken into account. On this basis, assessment of dose loads on the crews under direct radiation of the emergency unit was given (Table 1).

The registry of the Institute of Aviation and Space Medicine included 101 army aviation pilots who were admitted to the Central Research Aviation Hospital at the end of April and the beginning of May, 1986. The radiation dose for this contingent was (28.3±8.4) cGy — the variation coefficient was 30%. At the same time, 29 persons (28.7%) — according to the data of indirect dose assessment — 24 persons (23.8%) received doses over 25 cGy. Dose differences identified based on direct measurements and indirect assessment were as follows: within 5 cGy — 10.3%; 10 cGy — 43.3; within more than 10 cGy — 57.7%. The excess by more than 10 cGy of indirect dosimetry indicators in comparison with the indicators of individual dosimeters was noted in 78 pilots — 39.7% of cases. During the period of work from April 27 to June 1, 1986 the crews of Mi-26 helicopters received high doses of radiation (see Table 1).

Flight personnel who were admitted to the Central Research Aviation Hospital for examination were divided into two subgroups: helicopter pilots without comorbidities (no diagnosis) and helicopter pilots with comorbidities (Table 2).

In the 1st subgroup, the mean values of leukocyte count were $(6.0\pm0.1)10^9$/l; red blood cell count, $(4.7\pm0.02)10^{12}$/l; platelet count, $(277.3\pm6.1)10^9$/l; in the 2nd subgroup these values were (6.4±0.2); (4.8±0.02) and (284.3±5.4) respectively. Relative lymphocytosis and reticulocyte reduction to the lower limit of normal were noted in 25% of cases in both subgroups.

During the period when the pilots passed the medical-flight commission at the Central Research Aviation Hospital, the structure of the diagnoses did not change. At the 1st regular medical-flight commission (June 1986 - May 1987) 23 pilots (28%) out of 81 received the following conclusion: "Healthy (without clinical and hematological manifestations)", in 58 of them diseases were diagnosed (Table 3).

After the 1st regular medical-flight commission (May 1987) 6 pilots were declared unfit for flying. Two of them had the diagnosis "urolithiasis", 4 — combined diagnoses, but the main, unifying diagnosis was "emotional and vegetative instability, prolonged neurotic state". At the second regular medical-flight commission the same conclusions about unsuitability for flying work were received by two more pilots. During the periods of passing the medical-flying commission at the Central Research Aviation Hospital (1986-1988) the quantitative blood indices changed little. However, relative lymphocytosis was noted in 50% of cases (the 1st medical-flight commission after work at the Chernobyl NPP) and 40% (the 2nd medical-flight commission). The number of reticulocytes remained at the lower limit of the norm. Thus, most blood analyses had no deviations from the norm, and the observed weakly pronounced shifts did not correlate with the radiation dose.

Against this background, a number of liquidators had increased emotional lability, irritability, rapid fatigue, headaches, dizziness, internal tension, sleep disorders, nightmares, withdrawal, decreased memory, impaired concentration, anxiety, etc. when performing the tasks. These symptoms increased with time (Table 4).

Although the detected borderline mental disorders were transient, in some liquidators they took on a compulsive character. Comparison of the dynamics of the number of liquidators with partial health deficiencies in the groups under analysis showed that the main increase in the morbidity among the exposed people occurred in the first 5 post-radiation years, while among non-exposed people it occurred in 1990-1993. Apparently, this can be explained by the fact that in 1986-1991 most of the liquidators underwent hospital examination, which contributed to earlier detection of diseases. The pilots of the control group underwent an extended examination only when they reached the age of 35, i.e. in 1990-1993. Nevertheless, the fact of prevalence of diseases in helicopter liquidators over those in the control group during all 15 years of observation is obvious (Figure).

During the three months of work to eliminate the consequences of the accident, 1,125 aircrew were exposed to radiation. The number of pilots exposed to over 25 cGy and hospitalized in medical organizations was 65 (5.8%); the number of those exposed to 21-25 cGy who were taken off the flight was 366 (32.5%); the number of those exposed to under 20 cGy who were discharged from the accident region was 673 (59.7%). It is noteworthy that in the 16-20 cGy dose 27.5% of the aviation personnel were suspended from flying. And at doses over 21 cGy 9.8% of the pilots were allowed to continue flying. This demonstrates that at that time the dosage accounting was imperfect, as well as the lack of unified tactics among doctors and commanders in deciding whether pilots should be allowed to continue flying persisted.

Fifteen years after participation in elimination of the consequences of the accident, the bulk of the flight personnel completed their professional activities. At the same time almost 90% of helicopter pilots had different diseases, among which diseases of cardiovascular (52%) and nervous (39%) system, musculoskeletal system (27%), gastrointestinal organs (21%), respiratory system (29%), sense organs (7%) and others prevailed. Experimental data and clinic of human radiation sickness demonstrate that exposure of the abdomen results in a pronounced primary reaction: vomiting, bloating, pronounced pain syndrome, sleep disturbance and other symptoms [1, 6, 7]. Therefore, on the path of the main flow of gamma radiation from the destroyed reactor when irradiating the helicopter from the lower hemisphere, a lead shield of 5 mm thickness (attenuation factor of 1.5) or more was placed on the seat cup. In combination with an additional shield an anti-radiation belt protecting the abdominal area made in the form of a cartridge with

*Таблица 1 / Table No. 1*

**Дозы облучения, полученные экипажами вертолетов в период с 27 апреля по 1 июня 1986 г.**

Exposure doses received by helicopter crews from April 27 to June 1, 1986

| Тип вертолета Helicopter type | Категория летного состава – число обследованных, чел. Category of flight personnel - number of surveyed persons, people | Средняя суммарная доза облучения, сГр Average total dose, cGy | Средняя продолжительность пребывания в зоне, дни Average length of stay in the zone, days |
|---|---|---|---|
| Ми-8 Mi-8 | Командир – 73 Commander –73 | 18,7±0,9 | 4,6±0,4 |
| | Штурман – 74 Navigator – 74 | 18,8±0,9 | 4,4±0,4 |
| | Борттехник – 74 Flight technician – 74 | 18,9±1,0 | 4,5±0,8 |
| Ми-6 Mi-6 | Командир – 47 Commander – 47 | 17,1±1,1 | 3,1±0,2 |
| | Правый летчик – 47 Right pilot — 47 | 15,9±1,1 | 3,0±0,2 |
| | Штурман – 45 Navigator – 45 | 15,5±1,1 | 3,0±0,2 |
| | Борттехник – 43 Flight technician –43 | 15,2±1,1 | 2,8±0,2 |
| | Бортрадист – 42 Radio operator – 42 | 14,8±1,1 | 2,7±0,2 |
| | Механик грузового отсека – 45 Cargo compartment mechanic – 45 | 16,0±1,0 | 2,8 ±0,2 |
| Ми-26 Mi-26 | Командир – 28 Commander – 28 | 22,0±0,9 | 4,9±0,7 |
| | Правый летчик – 28 Right pilot – 28 | 20,0±1,1 | 5,1±0,7 |
| | Штурман – 28 Navigator – 28 | 19,0±1,2 | 5,0±0,7 |
| | Борттехник – 25 Flight technician – 25 | 22,5±1,2 | 4,5±0,7 |
| | Механик грузового отсека – 26 Cargo compartment mechanic – 26 | 25,3±2,1 | 4,5±0,6 |
| Ми-24 Mi-24 | Командир – 34 Commander – 34 | 18,6±1,3 | 5,1±0,4 |
| | Летчик-оператор – 34 Operator pilot –34 | 18,6±1,3 | 5,1±0,3 |
| | Дозиметрист – 10 Dosimetrist –10 | 24,3±2,1 | 4,5±0,6 |
| | Борттехник – 34 Flight technician –34 | 18,7±1,2 | 5,0±0,3 |

*Таблица 2 / Table No. 2*

**Состояние периферической крови у 81 летчика, проходившего обследование в ЦНИАГ в мае 1986 г.; ноябре 1986 г. – январе 1987 г. ; июне 1987 г. – апреле 1988 г.**

Peripheral blood condition in 81 pilots who were examined at the Central Research Aviation Hospital in May 1986; November 1986 to January 1987; June 1987 to April 1988

| Показатель Indicator | Обследованные лётчики без диагноза Examined pilots without a diagnosis | | | Обследованные лётчики с диагнозом Examined pilots with a diagnosis | | |
|---|---|---|---|---|---|---|
| | май / May1986 | ноябрь/Nov1986 – январь/ Jan1987 | июнь/June 1987– апр. /Apr 1988 | май / May1986 | ноябрь/Nov1986 – январь/ Jan1987 | июнь/June 1987– апр. /Apr 1988 |
| Гемоглобин, г/л Hemoglobin, g/l | 154,2±1,0 | 150,6±1,0 | 150,3±1,5 | 157,5±0,8 | 152,3±0,9 | 152,9±0,9 |
| Эритроциты, $10^{12}$/л Erythrocytes, $10^{12}$/l | 4,7±0,02 | 4,6±0,05 | 4,6±0,05 | 4,8±0,02 | 4,6±0,03 | 4,6±0,03 |
| Ретикулоциты, 0/00 Reticulocytes, 0/00 | 2,6±0,1 | 2,7±0,3 | 2,9±0,4 | 2,6±0,2 | 2,4±0,2 | 2,9±0,4 |
| Тромбоциты, $10^9$/л Platelets, $10^9$/l | 277,3±5,1 | 290,9±8,2 | 272,0±12,3 | 284,3±5,4 | 288,9±5,9 | 289,0±8,4 |
| Лейкоциты, $10^9$/л Leucocytes, $10^9$/l | 6,0±0,1 | 7,3±0,4 | 6,6±0,2 | 6,4±0,2 | 6,5±0,2 | 6,4±0,2 |
| Нейтрофилы - палочкоядерные, % Stab neutrophils, % | 1,7±0,1 | 1,7±0,4 | 1,2±1,2 | 1,1±0,1 | 1,0±0,1 | 1,4±0,2 |
| Нейтрофилы - сегментоядерные, % Segmented neutrophils, % | 54,7±0,9 | 53,7±2,0 | 53,6±1,3 | 55,0±1,1 | 54,1±1,2 | 53,6±1,1 |
| Эозинофилы, % Eosinophils,% | 3,3±0,2 | 3,1±0,7 | 3,4±0,4 | 2,5±0,1 | 2,9±0,3 | 2,8±0,3 |
| Базофилы, % Basophils,% | 0 | 0,04±0,02 | 0,05±0,01 | 0 | 0,04±0,03 | 0,06±0,03 |
| Лимфоциты, % Lymphocytes,% | 36,0±0,09 | 37,3±1,8 | 36,8±1,5 | 35,9±0,9 | 37,1±1,1 | 36,6±1,0 |
| Моноциты, % Monocytes,% | 5,1±0,2 | 4,1±0,5 | 4,8±0,5 | 5,2±0,2 | 5,0±0,3 | 5,5±0,3 |
| СОЭ, мм/ч ESR, mm / h | 5,0±0,3 | 5,0±0,5 | 4,6±0,5 | 4,8±0,2 | 4,3±0,3 | 4,9±0,3 |

interchangeable lead inserts of 198×77 mm size and 5 mm thickness of each plate was used [1]. In flight, the spatial orientation of the physical protection with respect to the radiation source was taken into account when the pitch angle changed from - 30° to +30° and the roll angle from 20° to 45°. Model measurements made by our associate A.A. Galkin showed that within these helicopter maneuvering angles, the belt attenuation multiplicity changes insignificantly. Direct measurements of doses in the abdominal area behind the belt during crew operations showed that when physical protection was applied, the radiation dose decreased by a factor of 2 to 3.

*Таблица 3 / Table No. 3*

**Доля летчиков с диагнозом до и после пребывания на ЧАЭС в апреле-мае 1986 г., %, по данным ВЛК**

Share of pilots with the diagnosis, before and after the Chernobyl accident in April-May 1986, %, according to medical board data

| Диагноз по системам Diagnosis by system | До аварии Before the accident | После аварии After the accident | |
|---|---|---|---|
| | 1985-1986 | 1986–1987 | 1987–1988 |
| Сердечно-сосудистая система Cardiovascular system | 26,0 | 31,0 | 32,0 |
| Желудочно-кишечный тракт Gastrointestinal tract | 14,0 | 17,0 | 20,0 |
| Центральная и периферическая нервная система Central and peripheral nervous system | 5,0 | 2,0 | 6,0 |
| ЛОР-система / ENT system | 3,0 | 23,0 | 27,0 |
| Органы зрения Organs of vision | 2,0 | 6,0 | 6,0 |
| Эндокринная система Endocrine system | 1,0 | 1,0 | 2,0 |
| Обмен веществ / Metabolism | 2,0 | 7,0 | 9,0 |
| Кожа / Skin | 3,0 | 1,0 | 2,0 |
| Опорно-двигательная система Musculoskeletal system | 1,0 | 5,0 | 5,0 |
| Органы дыхания Respiratory system | 1,0 | 2,0 | 2,0 |
| Всего с диагнозом Total with diagnosis | 53,0 | 72,0 | 75,0 |

During operation, the dose rate in helicopter cabins reached 2-4 Gy/h, and the probability of pilots' overexposure was quite high. Therefore, during the first day of accident elimination the pilots took cystamine in tablets at a dose of 1.2 g after breakfast 40-60 min before the flight. As a result, more than half of the pilots complained of discomfort, nausea and sweating 1 hour after taking cystamine. In this connection the radio-protector indralin — developed by D.I. Mendeleev Moscow Institute of Chemical Technology, the Institute of Aviation and Space Medicine and the Institute of Biophysics of the USSR Ministry of Health — was used instead of cystamine. The drug was manufactured in tablets and provided by the Institute of Biophysics. This drug was used in flights requiring a high level of coordination to stabilize the helicopter while hovering over the "crater" at an altitude of 200 m for 7-20 min. Indralin was taken orally in tablets with a dose of 0.45 g. M.V. Vasin monitored the intake of the drug and the pilots' well-being. After taking the radio-protectant, the crew members did not note any sensations, except for weak manifestations of parasthesia in the face. In their opinion, the drug had no effect on the operator's activity while hovering over the "crater" of the reactor. Laboratory studies performed 7-15 days after the intake of radioprotector during the stay of 7 pilots in Central Research Aviation Hospital did not reveal any functionally significant changes in blood parameters.

From clinical and etiological points of view, the characterization of disease nosology as a disqualifying factor of

*Таблица 4 / Table No. 4*

**Результаты психологического обследования летного состава через 5 лет после выполнения задания на радиационно-загрязненной местности**

Results of psychological examination of flight personnel 5 years after a mission in a radioactively contaminated area

| Группа Group | Возраст, лет Age, years | Доза облучения, сГр Radiation dose, cGy | Личностная тревожность, ед. Personal anxiety, units | Эмоциональная реактивность, ед. Emotional reactivity, units | Самооценка ночного сна, ед. Self-reported night sleep evaluation, units | Наркологический статус, ед. Drug status, units |
|---|---|---|---|---|---|---|
| 1-я 1st | 33,9±0,5 (79) | 26,2±0,8 (79) | 42,8±0,8** (74) | 352,4±28,3 (74) | 4,8±0,12* (66) | 20,7±1,1* (75) |
| 2-я 2nd | 34,4±0,7 (41) | 14,4±1,1 (39) | 39,6±1,3 (35) | 273,3±53,9 (16) | 5,1±0,12 (41) | 17,1±1,13 (40) |
| 3-я 3th | 34,4±0,8 (39) | 30,8±1,1 (38) | 42,0±1,1 (37) | 379,8±42,7 (34) | 4,8±1,7 (37) | 20,5±1,5 (36) |
| 4-я 4th | 33,2±1,2 (82) | 17,9±0,7 (78) | 41,6±0,9 (72) | 272,2±57,7 (15) | 4,9±0,97 (77) | 19,0±0,96 (79) |
| 5-я 5th | 32,3±1,1 (28) | – | 38,8±1,35 (28) | 312,0±24,6 (28) | 5,4±0,62 (28) | 16,2±1,7 (28) |

Примечание: 1-я группа – выполнявшие задание в острый период аварии; 2-я – выполнявшие задание в промежуточный период аварии; 3-я – облученные в дозе более 25 сГр; 4-я – облученные в дозе менее 25 сГр; 5-я группа (контрольная) – необлученный летный состав
Достоверность различий *, ** – между группами 1-й и 2-й, 3-й и 4-й для P<0,05 и P<0,1 соответственно; ± к 5-й группе для P<0,05
В скобках – число обследованных

Note: Group 1 -those who performed the task in the acute period of the accident; Group 2 - those who performed the task in the intermediate period of the accident; Group 3 - those exposed to over 25 cGy; Group 4 - those exposed to less than 25 cGy; Group 5 (control) - unexposed aircrew members
Significance of differences *, ** – between Group 1 and Group 2, Group 3 and Group 3, P<0.05 и P<0.1 respectively; ± to Group 5, P<0.05
In parentheses – number of surveyed

flight personnel is of interest [1, 7, 12, 13]. The nature of the data we obtained confirms the presence of a clear difference between the liquidators and pilots of the control group. Fifteen years of observation showed that in the control group a large proportion of diseases were diseases of the musculoskeletal system. The liquidators group was characterized by the formation of chronic diseases whose pathogenetic mechanism was psychogenic-traumatic. In 1999 35% of helicopter liquidators with a diagnosis were subjected to disqualification due to changes in the neuro-psychic sphere (in the control group — 14%). In addition, the neuropsychiatric component was present in all somatic diseases and even in clinically healthy individuals. A major role in the disqualification of helicopter liquidators is played by cardiovascular diseases (45%), and over 15 years their component has remained virtually unchanged. Thus, in 1986, due to disqualification by disease, the proportion of cardiovascular disease was 48%, in 1991 - 55%. In the control group in 1986, the proportion of cardiovascular disease in the disqualified population was 55%; in 1991 it was 24%; in 1999 it was only 19%. In 1986, gastrointestinal diseases accounted for 26% of disqualifications in the liquidators and 18% in the control group. By the end of observation disqualification for gastrointestinal diseases decreased to 10%, in the control group — up to 7%. In 1999 in the group of liquidators with diagnoses were disqualified for diseases of the musculoskeletal system — 10%, while in the control group these diseases gave the highest percentage of disqualifications: in 1991 — 24%, in 1999 — 27%.

Flight personnel activities associated with participation in liquidation of the Chernobyl accident took place under conditions of emotional tension and radiation exposure, which pilots had not previously encountered. In addition to external beta- and gamma-exposure, the liquidators were

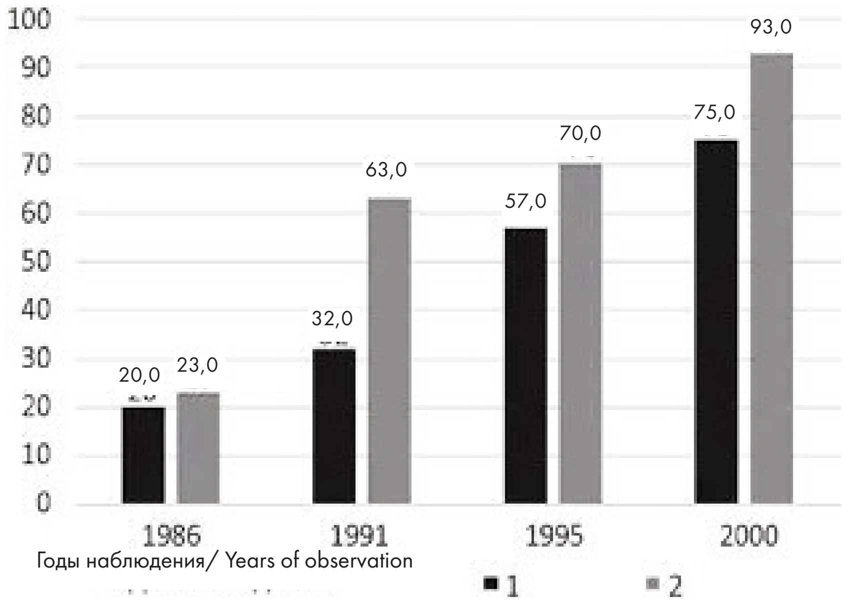


**Рисунок.** Характеристика общего здоровья ликвидаторов за 15 лет после аварии.
По горизонтали – годы наблюдения; по вертикали – доля (%) летчиков, имевших диагноз заболевания;
1 – контрольная группа; 2 – группа ликвидаторов
**Figure.** Characteristics of the general health of liquidators in 1986-2000. Horizontal — years of observation; vertical — percentage of airmen diagnosed with disease; 1 — control group; 2 — liquidator group

exposed to internal radiation exposure to alpha-, beta- and gamma-emitting radionuclides incorporated as a result of their inhalation and ingestion into the body during the mission. For example, after the approach of two or three helicopters, a continuous dust cloud at least 30 m high rose over the loading area, and this lasted from April 29 to May 6 for 16 hours a day [3, 4, 7].

In the early period of the liquidation work, the influence of such a stress factor as the fear of overexposure was not excluded. All these factors together determined the subsequent changes in the mental sphere of pilots both in the nearest and in the more distant period. The strength of the impact of emergency radiation environment on the mental state of pilots, including their motivational sphere, is evidenced by the answers to the question: "Is there a desire to take part in similar operations in the future?" Only 23% of respondents answered "yes" affirmatively and without hesitation. The majority (68%) answered "no." In the group of surveyed pilots, 39.5% had an increase in reactive anxiety above 45 units (exceeding the norm 1,5 times), increase of emotional reactivity, decrease of emotional stability level (according to 16-factorial personality survey) and there was vegetative functions lability — increase of tremor, fluctuations of arterial pressure. These shifts in mental status reduce efficiency and reliability of professional activity, affect flight safety and serve as a serious prerequisite for the development of psychosomatic diseases in flight personnel.

At insignificant radiation doses, it is very difficult to differentiate deviations caused by a nonspecific influence of an extreme situation from deviations related to a specific effect of radiation. One can rather speak of a combined effect of emergency factors on the organism of liquidators [1, 12, 14]. And the connection between the value of the dose received and changes in the neuro-emotional state has a unidirectional character. Thus, a positive correlation was noted between the exposure dose and the level of reactive anxiety (r=0.22), emotional stability (r=0.27) and reactivity (r=0.46).

**Conclusion**

In the nearest period after work in the center of a radiation accident the phenomena of neuroticism were noted in the flying personnel. With the lapse of time the liquidators changed their assessment of the situation of radiation exposure. One year after the accident, 60% of the pilots believed that participation in the events allowed them to believe in themselves, in their strength and abilities; 50% thought that they had acquired professionally important qualities; 30% considered the experience gained valuable; 15% of the pilots after participation in the events gained a new, socially more meaningful outlook on life. In 90.5% of the pilots, participation in the accident elimination did not decrease their motivation for flying work. Almost all of those surveyed were ready to work in such conditions. At the same time, one in three noted that their state of health had deteriorated over the past time, which was expressed in increased fatigability (62.5%) and reduced potency (37.5%). According to the data obtained with the same contingent who did not take part in the Chernobyl events, the disorders were much less widespread.

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***Original article***



# APPLICATION OF REGENERATIVE CELL TECHNOLOGIES IN THE TREATMENT OF SEVERE LOCAL RADIATION INJURIES IN VICTIMS OF EMERGENCY SITUATIONS: FROM THE EXPERIENCE OF THE SPECIALISTS OF THE FEDERAL MEDICAL BIOPHYSICAL CENTER NAMED AFTER A.I.BURNAZYAN OF THE FEDERAL MEDICAL AND BIOLOGICAL AGENCY OF RUSSIA

T.A.Astrelina[1], A.V.Aksenenko[1], I.V.Kobzeva[1], V.A.Brunchukov[1], D.Yu.Usupzhanova[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** It has been noted that one of the most common types of radiation injuries when a person is exposed to ionizing radiation is radiation burns — severe local radiation injuries.
*The aim of the study* is to apply stromal and vascular fraction of adipose tissue to increase the efficiency of complex therapy for local radiation lesions.
*Materials and methods of the study.* In 2017-2019, 7 patients (all male; mean age — (54.83±9.41) years) with local radiation lesions of the skin — ulcerative-necrotic lesions of the skin and underlying tissues — were treated at the Federal Medical Biophysical Center named after A.I. Burnazyan of FMBA of Russia. For more than 6 months the patients received conventional conservative therapy of local radiation lesions and a single injection of cell suspension of autologous cells of stromal-vascular fraction of adipose tissue — the average number of cells was (60.33×106±64.04).
*Results of the study and their analysis.* All patients had no serious adverse events and reactions associated with the introduction of autologous regenerative cells of adipose tissue. During the whole period of observation after stromal-vascular fraction of adipose tissue was injected, late radiation ulcers remained without signs of inflammation and infiltration. The patients were discharged from the hospital in satisfactory condition.
According to the authors, the use of stromal-vascular fraction of adipose tissue in local radiation lesions provides favorable conditions: to increase the effectiveness of complex therapy; to reduce healing time of the wound surface; to regulate and activate immune and reparative processes in the dermis; to restore the damaged vascular network, lost skin without severe scarring changes; to heal and achieve a satisfactory result, decent quality of life of patients.

**Key words:** *ccell therapy, emergencies, radiation, regenerative cell technologies, severe local radiation injuries, stromal-vascular fraction of adipose tissue, victims*

**Conflict of interest.** The authors declare no conflict of interest

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***Оригинальная статья***



# ПРИМЕНЕНИЕ РЕГЕНЕРАТИВНЫХ КЛЕТОЧНЫХ ТЕХНОЛОГИЙ ПРИ ЛЕЧЕНИИ ТЯЖЁЛЫХ МЕСТНЫХ ЛУЧЕВЫХ ПОРАЖЕНИЙ У ПОСТРАДАВШИХ В ЧРЕЗВЫЧАЙНЫХ СИТУАЦИЯХ: ИЗ ОПЫТА РАБОТЫ СПЕЦИАЛИСТОВ ФЕДЕРАЛЬНОГО МЕДИЦИНСКОГО БИОФИЗИЧЕСКОГО ЦЕНТРА ИМ. А.И.БУРНАЗЯНА ФМБА РОССИИ

Т.А.Астрелина[1], А.В.Аксененко[1], И.В.Кобзева[1], В.А.Брунчуков[1], Д.Ю.Усупжанова[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** Отмечено, что одним из наиболее распространенных видов радиационных поражений при воздействии ионизирующего излучения на человека являются радиационные ожоги – тяжелые местные лучевые поражения (МЛП).
*Цель исследования* – применение стромально-васкулярной фракции (СВФ) жировой ткани (ЖТ) для повышения эффективности комплексной терапии при МЛП.
*Материалы и методы исследования.* В 2017–2019 гг. в Федеральном медицинском биофизическом центре им. А.И.Бурназяна ФМБА России были пролечены 7 пациентов (все – мужчины; средний возраст – (54,83±9,41) года) с МЛП кожных покровов – язвенно-некротическим поражением кожи и подлежащих тканей. В течение более 6 мес пациенты получали общепринятую консервативную терапию МЛП и однократное введение клеточной суспензии аутологичных клеток стромально-васкулярной фракции жировой ткани – среднее количество клеток составляло (60,33×106±64,04).
*Результаты исследования и их анализ.* У всех пациентов не было отмечено серьезных нежелательных явлений и реакций, связанных с введением аутологичных регенеративных клеток жировой ткани. За весь период наблюдения после введения СВФ ЖТ поздние лучевые язвы оставались без признаков воспаления и инфильтрации. Пациенты были выписаны из стационара в удовлетворительном состоянии.
По мнению авторов, применение СВФ ЖТ при МЛП обеспечивает благоприятные условия: для повышения эффективности комплексной терапии; сокращения сроков заживления раневой поверхности; регуляции и активации иммунных и репаративных процессов в дерме; восстановления поврежденной сосудистой сети, утраченных кожных покров без грубых рубцовых изменений; для заживления и достижения удовлетворительного результата, достойного качества жизни пациентов.

**Ключевые слова:** *клеточная терапия, пострадавшие, радиация, регенеративные клеточные технологии, стромально-васкулярная фракция жировой ткани, тяжелые местные лучевые поражения, чрезвычайные ситуации*

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***Contact information:***
***Tatiana A. Astrelina*** **–** Dr. Sc. (Med.), Assoc. Prof.; Head of Center for Biomedical Technologies, Head of the Department of Regenerative Medicine, Hematology
**Address:** 23, Marshala Novikova str., Moscow, 123098, Russia
**Phone:** +7 (916) 532-56-77
**E-mail:** t_astrelina@mail.ru

***Контактная информация:***
***Астрелина Татьяна Алексеевна*** **–** доктор медицинских наук, доцент; руководитель Центра биомедицинских и аддитивных технологий, зав. кафедрой регенеративной медицины, гематологии
**Адрес:** Россия,123098, г. Москва, ул. Маршала Новикова, д. 23
**Тел.:** +7(916) 532-56-77
**E-mail:** t_astrelina@mail.ru

## Introduction

One of the most common types of radiation injuries when a person is exposed to ionizing radiation is radiation burns — severe local radiation injuries. Local radiation injuries to the skin are common in radiation accidents and incidents involving sources of ionizing radiation.

Thus, on the territory of the former USSR in 1950-2000 there were 349 radiation accidents accompanied by the development of radiation injuries. Acute radiation sickness combined with local radiation injuries was diagnosed in 747 people. In the USA in 1944-2000 there were 246 radiation accidents accompanied by development of local radiation injuries of various localizations (92%) in 793 people; in China in 1949-1988 there were 14 major radiation accidents accompanied by development of local radiation injuries in 47 individuals. [1-8].

According to numerous studies, skin changes due to radiation damage occur early due to genetic damage to stem and proliferating epidermal cells due to reduced reparative processes. Damage of less radiosensitive cell and tissue elements is also important: vascular endothelium, fibroblasts, elastic and smooth muscle sheaths. A characteristic feature of clinical course of local radiation lesions is a high probability of late radiation complications. They develop 6 months and more after the period of visible recovery.

Local radiation lesions are very difficult to treat. Conservative methods of treatment of non-healing chronic radiation ulcers are ineffective. Surgical intervention is often required, which is not always possible because of the condition of the victim's body.

In this regard, the development of new ways to improve the complex conservative treatment of local radiation lesions of the skin is an important task of modern medicine.

One of promising methods of treatment of local radiation lesions is cell therapy. Its use in clinical practice in the complex treatment of local radiation lesions will reduce the healing time of ulcerous defects and improve the quality of life of patients. For cell therapy are used: mesenchymal stromal cells from various sources; autologous minimally manipulated products (regenerative cells) based on adipose tissue; paracrine factors derived from cultured stem cells, etc.

The successful use of mesenchymal stromal cells in the treatment of radiation burns is due to their secretory activity. This activity is related to their production of a wide range of cytokines and growth factors. Besides, mesenchymal stromal cells have immunosuppressive, anti-inflammatory and trophic effects [9-12]. Cases of successful application of mesenchymal stromal cells in the treatment of radiation ulcers caused by X-rays have been described [13, 14]. In clinical application the safety of cell therapy has been proved. It is also established that transplantation of mesenchymal stromal cells interrupts the pathological inflammatory phase of inflammation, leading to an acceleration of the healing rate. However, the proposed method of treatment requires long-term cultivation of mesenchymal stromal cells.

At the present time in plastic surgery and clinical practice for the treatment of bone defects and soft tissue volume, diseases of musculoskeletal system and other diseases adipose tissue — subcutaneous fatty tissue — is actively used. The effect of regenerative cells (stromal and vascular fraction of adipose tissue) is realized due to their differentiation and replacement of damaged tissue areas, production of paracrine factors providing immunomodulatory effect, prevention of cell death by apoptosis mechanism, neoangiogenesis, fibrous and connective tissue remodeling [15-17]. Studies on laboratory animals at the State Research Center — A.I. Burnazyan Federal Medical Biophysical Center of the Federal Medical and Biological Agency of Russia (hereinafter — A.I. Burnazyan Federal Biophysical Center) showed that the use of regenerative cells of adipose tissue improves the course of local radiation lesions of the skin. It also accelerates wound healing processes due to improved neoangiogenesis and increased proliferation of fibroblasts after local X-ray irradiation in the experiment [18, 19]. All this points to the possibility of successful application of adipose tissue cells in severe local radiation lesions.

Thus, the data of the studies demonstrate an important role of regenerative medicine and cell technologies in the treatment of local radiation lesions. Autologous regenerative cells of stromal and vascular fraction of adipose tissue appear to be the most promising for clinical application. They have the ability to differentiate due to their heterogeneity and secrete a huge range of cytokines and growth factors that play an important role in tissue regeneration. Studies on laboratory animals have demonstrated high efficacy and safety of application of autologous regenerative cells of stromal and vascular fraction of adipose tissue in treatment of severe local radiation lesions. However, there are no data on clinical application of autologous regenerative cells of stromal and vascular fraction of adipose tissue in the treatment of local radiation lesions in the victims. All this points to the possibility of successful application of regenerative cells of adipose tissue in the treatment of severe local radiation lesions in humans.

**The aim of the study** is to apply stromal and vascular fraction of adipose tissue to increase the efficiency of complex therapy for local radiation lesions.

**Materials and methods.** In 2017-2019 7 patients with local radiation lesions of the skin — ulcerative-necrotic lesions of the skin and underlying tissues were treated at the A.I. Burnazyan Federal Medical and Biological Center of the Federal Medical and Biological Agency of Russia. All patients were men, mean age — (54,83±9,41) years, mean body weight — (72,67±16,12) kg, mean height — (175,65±8,07) cm, mean body surface area — (1,95±0,17) m2, mean body mass index (BMI) — (26,37±3,23). For more than 6 months the patients received conventional conservative therapy of local radiation lesions.

All patients underwent laboratory tests (clinical blood test, serological reactions, biochemical blood test, coagulogram, clinical urinalysis) and instrumental methods of investigation.

All patients had the results of laboratory indices and instrumental methods of investigation within the normal range and there were no contraindications for adipose tissue sampling and for application of stromal-vascular fraction of adipose tissue.

Indications for the use of stromal-vascular fraction of adipose tissue in patients with local radiation lesions:

1. History of exposure to ionizing radiation.
2. Ulcerative-necrotic lesions/ lesions of the skin and underlying tissues lasting more than 6 months.
3. A negative urine pregnancy test result, consent to abstain from sexual intercourse completely or to use reliable contraception for women of reproductive age for the duration of the study.
4. Patients read the information sheet and signed the informed consent form.

Contraindications for the use of stromal and vascular adipose tissue fraction in patients with local radiation lesions:

1. Refusal of a patient with local radiation lesion or of his close relatives to use stromal-vascular fraction of adipose tissue.
2. Chronic diseases of internal organs in subcompensated or decompensated forms.
3. Delayed physical development.
4. Cancer registered in the last 5 years.
5. Depression or other clinically significant mental illness.
6. Significant weight loss (>10% of body weight in the previous year) of unspecified etiology.
7. Active infectious and inflammatory diseases.
8. Pregnancy or breastfeeding period.


**Рис. 1.** Схема получения регенеративных клеток жировой ткани для клинического применения
**Fig. 1.** Fig. 1. Algorithm of decision making about the necessity of using regenerative cells of stromal-vascular fraction of adipose tissue in local radiation damage in medical facilities

9. Drug abuse, current or history of drug and/or alcohol abuse.
10. Therapy with immunosuppressive drugs, including chemotherapy, in the last 5 years.
11. Autoimmune diseases requiring regular immunosuppressive therapy.
12. Clinically significant abnormalities in the results of laboratory tests.

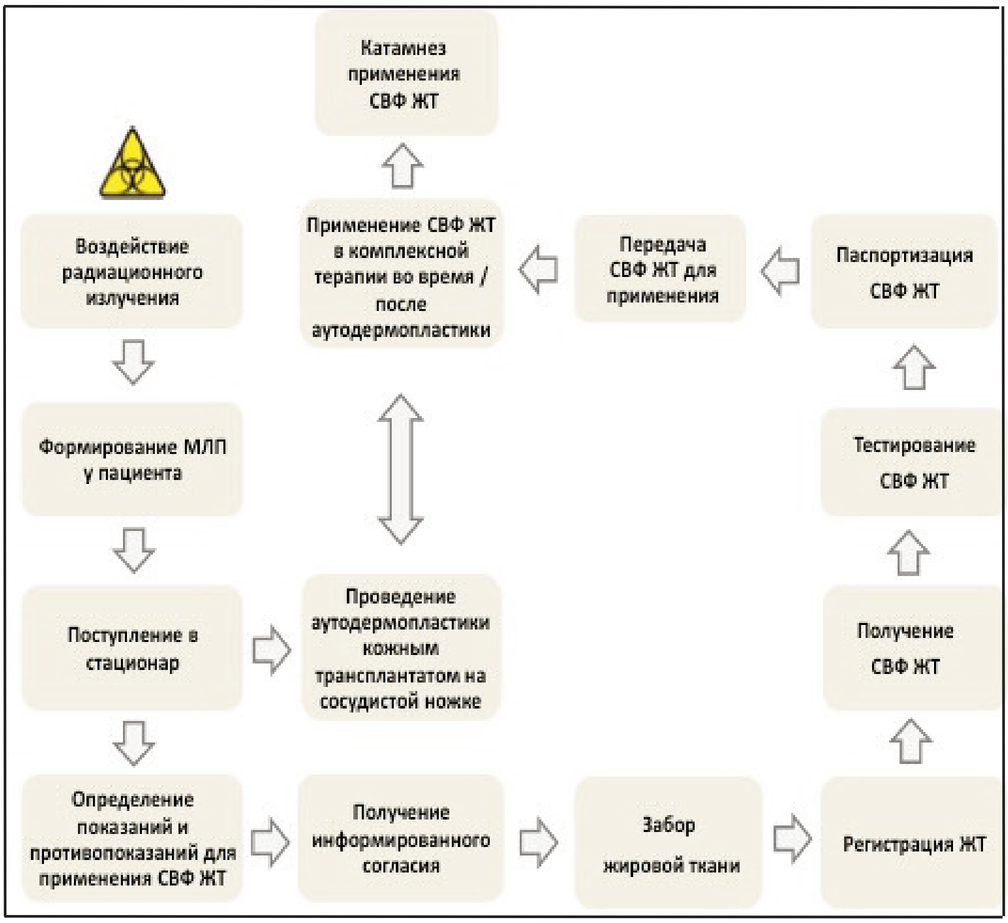


**Рис. 2.** Алгоритм принятия решения о необходимости применения регенеративных клеток СВФ жировой ткани при лечении пациента с МЛП в лечебной медицинской организации
**Fig. 2.** Scheme of obtaining regenerative cells of adipose tissue for clinical use

13. Patients receiving anticoagulants due to any disease, as well as patients who received anticoagulants for at least 1 h before lipoaspiration.

14. Patients who are or were receiving glycoprotein IIB/IIIA inhibitors before the study.

15. Patients with contraindications for local anesthesia or with a history of allergic reactions to local anesthetics.

16. Confirmed carriers of HIV or hepatitis B or C.

17. Presence of any other comorbidities that put the patient's safety at risk for participation in the study or will affect the safety assessment, including: diabetes mellitus; obesity — BMI > 35 kg/m2; bronchial asthma; epilepsy, migraine, seizures or other central nervous system disorders, including a history of them; cardiovascular and cerebro-vascular diseases, including a history of them; presence of thrombosis — venous and/or arterial, thromboembolism or thrombophlebitis — current or history of it.

Basic requirements for safety and efficiency of adipose tissue sampling, its processing, obtaining stromal-vascular fraction of adipose tissue and its application:

1. Manipulations for taking biological material of adipose tissue and isolation of stromal and vascular fraction of adipose tissue must be performed by qualified personnel in sterile conditions.

2. Manipulations with biological material must be performed in sterile rooms with appropriate certified equipment and consumables.

3. The list of necessary equipment should include: laminar flow cabinet, $CO_2$ incubator, cell counter, centrifuge, cytofluorimeter, disposable consumables, and other reagents.

4. It is necessary to create strictly controlled and standardized methods and procedures for processing and obtaining stromal-vascular fraction of adipose tissue — reagents, enzymes, etc.

5. Testing of stromal-vascular fraction of adipose tissue, including number and viability of cells, immunophenotyping of surface antigens, sterility control, and passportization.

6. Application (local injection) of stromal-vascular fraction of adipose tissue complex for treatment of local radiation lesions should be performed by qualified personnel in sterile conditions.

After signing an informed consent to obtain biological material of adipose tissue for cell therapy, aspiration liposuction in the lower third of the anterior abdominal wall was performed in the operating room under general anesthesia. The average volume of lipoaspirate adipose tissue was (42.32±13.98) g. For clinical use, adipose tissue was washed, enzymatically treated with collagenase, centrifuged, and stromal and vascular fractions of adipose tissue were obtained. The number of cells in the stromal-vascular fraction of adipose tissue was counted using an automatic Counterss Invitrogen cell counter (Invitrogen). The average number of cells in the stromal-vascular

*Таблица / Table*

**Распределение пациентов по этиологии и дозе радиационного поражения**
Distribution of patients by etiology and doses of radiation exposure

| Пациент Patient | Возраст, лет Age, years | Год, получения радиационного поражения Year of radiation exposure | Вид радиационного поражения Type of radiation damage | Этиология радиационного поражения Etiology of radiation damage | Доза радиационного поражения Dose of radiation exposure | | |
|---|---|---|---|---|---|---|---|
| | | | | | предполагаемая доза, Гр Estimated dose, Gy | цитогенетика, Зв Cytogenetics, Sv | ЭПР эмали зуба, Гр Electron paramagnetic resonance of tooth e enamel, Gy |
| К. / K. | 57 | 1990 | Пучок электронов Beam of electrons | Нарушение техники безопасности на производстве Violation of industrial safety | НД - нет данных N/A - no data available | 0,30 | 0,11 |
| Ф. / F. | 48 | 2000 | Иридий-192 Iridium-192 | Нарушение техники безопасности на производстве Violation of industrial safety | 30–70 Частота дицентриков - 1,75Гр Dicentric frequency - 1.75 Gy Кариология - 2,0 Гр Karyology -2.0 Gy Нейтрофилы - 1,2 Гр Neutrophils -1.2 Gy | 1,09 | 2,6±0,2 |
| Н. / N. | 70 | 2006 | Рентген X-ray | Медицинское лечение Medical treatment | 2,7 | 1,4 | НД / N/A |
| Л. / L. | 57 | 2007 | Иридий-192 (60 Кюри 11,2 ТБк (активность 302 Ки) Iridium-192 (60 Curie 11.2 TBq (activity 302 Ci) | Нарушение техники безопасности на производстве Violation of industrial safety | 25–30 | 0,29 | НД / N/A |
| Л. / L. | 48 | 2008 | Иридий-192 Iridium-192 | Нарушение техники безопасности на производстве Violation of industrial safety | 30-50 | 0,48 | НД / N/A |
| Д. / D. | 45 | 2012 | Иридий-192 Iridium-192 | Нарушение техники безопасности на производстве Violation of industrial safety | НД / N/A | 0,28 | НД / N/A |
| Л. / L. | 78 | 2013 | Гамма Gamma | Медицинское лечение Medical treatment | 60 | НД / N/A | НД / N/A |

fraction of adipose tissue was 60.33x(106±64.04) per sample. Immunological evaluation (immunophenotype) and viability were performed by flow cytofluorimetry — BD FACS Canto II, USA. Monoclonal antibodies to the following antigenic markers were used to examine the phenotype of the stromal and vascular fraction cells: CD45, CD34, CD31, CD105, CD73, CD90, CD146, and a 7-ADD viability dye (Fig. 1). The staining was performed according to the manufacturer's recommendations.

**Results of the study and their analysis.** To decide on the necessity of using regenerative cells of adipose tissue in patients with local radiation lesions we used the developed algorithm (Fig. 2). Patients with radiation lesions of the skin and underlying tissues with ulcerative-necrotic lesions of the skin and underlying tissues due to distant consequences of local radiation lesions of varying severity and with duration of its course over 6 months — were hospitalized in the hospital (Table). Such patients underwent standard local conservative therapy of local radiation lesions in combination with radical necrectomies. In case of impaired gliding function of tendons, a comprehensive standard therapy for its restoration was performed.

Before the stromal-vascular fatty tissue fraction therapy, an in vivo pathological-anatomical examination of biopsy (surgical) material in each patient showed an erosive-ulcerous epidermal defect with scarring changes in the dermis and the presence of focal lymphocytic infiltrates in it. Degenerative changes of derma, its sclerosis, coarsening of derma collagen were observed along the periphery of the erosive-ulcerous area. Hypertrophied nerve trunks resembling neuromas of tactile endings were found in deep parts of the dermis. The bone was represented by cancellous bone with enlarged medullary cavities filled with fatty tissue. No reliable morphological signs of osteomyelitis were detected. The conclusion was that these histological changes could be a manifestation of late post-radiation dermatitis with erosive-ulcerative skin changes and scarring-sclerotic changes of the deep tendon.

After signing the informed consent, adipose tissue was taken by syringe liposuction in the lower third of the anterior abdominal wall under operating room conditions. See Fig. 1 for the technique of isolation of regenerative cells of adipose tissue for clinical use.

Autologous regenerative cells of the stromal and vascular adipose tissue fraction were isolated. The obtained cells of stromal and vascular fraction of adipose tissue were sterile when tested for sterility (infectious safety). The stromal-vascular fraction of adipose tissue consisted of stromal cells (15-30%, of which 3% were stem cells and progenitor cells — positive expression of CD105, CD90, CD73); endothelial cells (10-20% — positive expression of CD31); blood cells (5-15% — positive expression of CD45); pericytes (3-5% — positive expression of CD146); hematopoietic stem cells (<0.1% — positive expression of CD34) — (Fig. 3). The viability of the stromal and vascular fraction of adipose tissue was (98.32±2.98)%.

Under aseptic conditions an insulin syringe with a 0.45mm×12mm 26 Gx½ needle was used to inject a single cellular suspension of autologous stromal and vascular fractions of adipose tissue in 10-15 points around the ulcerous surface at a depth of 3-5 mm (Fig. 4). The volume of injected cell suspension containing autologous regener-

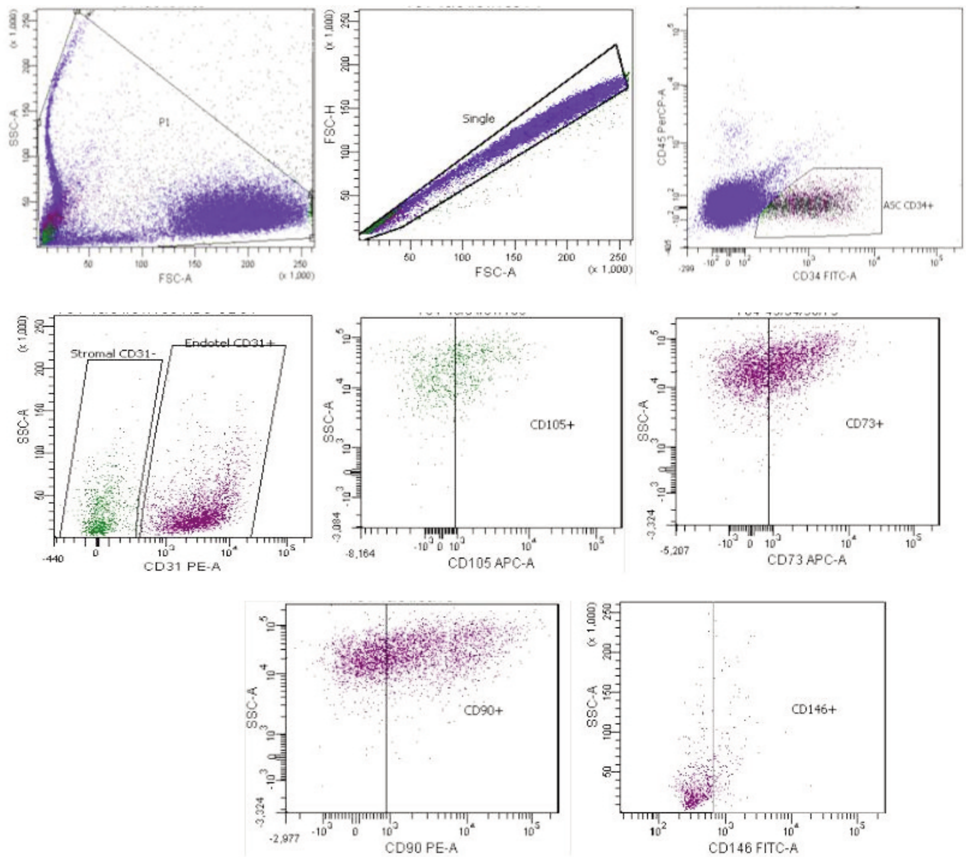


**Рис. 3.** Иммунологическая оценка регенеративных клеток жировой ткани: CD45+CD34+/CD31+/CD105+/CD73+/CD90+/CD146+

**Fig. 3.** Immunological evaluation of regenerative adipose tissue cells: CD45+CD34+/CD31+/CD105+/

**Рис. 4.** Введение клеточной суспензии СВФ ЖТ
**Fig. 4.** Injection of cell suspension of adipose tissue stromal-vascular fraction

ative cells of adipose tissue is 5 ml. The recommended dose of autologous regenerative cells of adipose tissue is 0.5-1.0 ml/cm$^2$.

All patients had local soreness and slight swelling in the area of injection without changes in vital functions and laboratory abnormalities after injection of a suspension of autologous regenerative cells of adipose tissue for one day. This phenomenon was regarded as a local tissue reaction to the injection. No adverse events, deviations of vital functions and laboratory parameters were registered during the entire period of observation. This can testify to the safety of introduction of autologous regenerative cells of adipose tissue in humans. There were no serious adverse events and reactions associated with the introduction of autologous regenerative cells of adipose tissue.

To ensure the patient's well-being and to prevent possible complications, the necessary registered medications were used in accordance with the treatment standards for the underlying disease.

In all 7 patients during the whole period of observation after injection of a suspension of autologous regenerative cells of the stromal and vascular fraction of adipose tissue, late radial ulcers remained without signs of inflammation and infiltration (Fig. 5). The patients were discharged from the hospital in a satisfactory condition.


**Рис. 5.** Последствия местного лучевого поражения до и через 6 мес после введения СВФ ЖТ: А – пациент Д.; Б – пациент К.; В – пациент Л.; Г –пациент Л.
**Fig. 5.** Consequences of local radiation lesions before and after the injection of adipose tissue stromal-vascular fraction after 6 months: A – Patient D., B – Patient K., C – Patient L., D – Patient L.

**Discussion of the results of the study.** The relevance of the study is determined by the complexity and duration of local radiation lesions treatment, large financial expenses for treatment, long loss of working capacity, need for rehabilitation and disability of patients. One of the cornerstones in the treatment of local radiation lesions is skin repair. Patients with local radiation lesions of the skin need surgical plastic interventions, since the independent process of epithelialization is impossible. The formation of ulcers, pathological scars and contractures, rejection of grafts significantly increase the duration of treatment process, worsen the results of treatment and quality of life. Therefore, the improvement of the system of medical care for patients with local radiation lesions is one of the pressing problems of modern surgery, which requires a search for new methods of treatment.

At present, necrectomy with one-stage or delayed autodermoplasty with a skin graft is used to heal the damaged skin. Autografting is considered to be the most acceptable variant of plasty. However, this kind of plasty does not always provide satisfactory functional and cosmetic results. One of the promising methods of treatment of skin lesions and its appendages is cell therapy, the use of which in clinical practice will reduce the period of graft engraftment and improve the quality of life of patients.

A known method of treating local radiation lesions of the skin using autotransplantation of adipose tissue obtained as a result of liposuction. However, the use of freshly isolated lipoaspirate without specific laboratory steps for its purification from blood cell elements and isolation of stromal-vascular fraction did not provide restoration of the regenerative potential of dermal cells and necessary vascularization of the skin [20].

Currently, adipose tissue is actively used in plastic surgery and clinical practice for the treatment of bone defects and soft tissue volume, diseases of the musculoskeletal system, etc. The effect of regenerative cells of adipose tissue is realized due to their differentiation and replacement of damaged tissue areas; production of paracrine factors providing immunomodulatory effect, prevention of cell death by apoptosis mechanism, neoangiogenesis, fibrous and connective tissue remodeling. The results of numerous studies on laboratory animals showed that the use of regenerative cells of adipose tissue improves the course of the inflammatory process, accelerates the healing of lesions by improving neoangiogenesis and enhancing the proliferation of fibroblasts. All this testifies to the possibility of successful application of adipose tissue cells in local radiation lesions of the skin.

The results of the present study showed that application of autologous regenerative cells of stromal and vascular fraction of adipose tissue contributed to activation of reparative processes in the dermis, reduction of the local inflammatory reaction, healing, acceleration of skin elasticity restoration with reduction of fibrosis severity.

Thus, in order to increase the efficiency of ulcer surface healing in local radiation lesions of the skin, the specialists of A.I. Burnazyan Federal Medical and Biological Center of the Federal Medical and Biological Agency of Russia suggest using own regenerative cells of the stromal and vascular fraction of adipose tissue during routine surgical treatments of the ulcer surface according to the developed algorithm. These cells and the growth factors and cytokines produced by them take part in reparative processes, in the restoration of the damaged vascular network, as well as in the regulation of immune processes. In our opinion, due to the high availability of obtaining adipose tissue in a sufficient volume from almost any patient, the possibility of using the obtained regenerative cells of the stromal and vascular fraction of adipose tissue immediately after their isolation without long-term cultivation will be of great importance when performing reconstructive-plastic operations.

## Conclusion

The presented algorithm of decision-making on the use and application of stromal-vascular fatty tissue fraction in patients with local radiation lesions provide favorable conditions: for increasing the efficiency of complex therapy; for reducing the healing time of the wound surface; for regulating and activating immune and reparative processes in the dermis; for restoring the damaged vascular network and lost skin without severe scarring changes; for healing and improving the quality of life of patients.

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**Original article**



# A RISK-BASED CAUSAL MODEL OF RISK FACTORS FOR INFECTION AMONG MEDICAL PERSONNEL INVOLVED IN THE CARE OF PATIENTS WITH THE NEW COVID-19 CORONAVIRUS INFECTION

E.A.Annenkova[1], O.A.Tikhonova[1], A.P.Biryukov[1], L.I.Baranov[1], I.G.Dibirgadzhiev[1], M.V.Sheyanov[1], O.A.Kasymova[1], O.V.Parinov[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** *TThe aim of the study* is to develop and apply a mathematical model for assessing the risks of contamination of medical personnel involved in providing medical care to patients with COVID-19 in a "red zone" environment.

*Materials and methods.* Based on the analysis of informative signs and information on working conditions in the infectious disease department of the A.I. Burnazyan Federal Medical Biophysical Center of the Federal Medical and Biological Agency of Russia, a decision-making support system was developed to provide an objective assessment of the risks of infection for medical personnel when providing medical care in the "red zone".

*Results of the study and their analysis.* The influence of various risk factors for infection of medical personnel involved in the provision of medical care to patients with new coronavirus infection COVID-19 was analyzed; the most significant risk factors were identified.

**Key words:** *dose-effect, mathematical model of infection risk assessment, medical personnel, new coronavirus infection COVID-19, patients, red zone*

**Conflict of interest.** The authors declare no conflict of interest

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**Оригинальная статья**



# РИСК-ОРИЕНТИРОВАННАЯ МОДЕЛЬ ПРИЧИННО-СЛЕДСТВЕННЫХ СВЯЗЕЙ ФАКТОРОВ РИСКА ЗАРАЖЕНИЯ МЕДИЦИНСКОГО ПЕРСОНАЛА, УЧАСТВУЮЩЕГО В ОКАЗАНИИ МЕДИЦИНСКОЙ ПОМОЩИ ПАЦИЕНТАМ С НОВОЙ КОРОНАВИРУСНОЙ ИНФЕКЦИЕЙ COVID-19

Е.А.Анненкова[1], О.А.Тихонова[1], А.П.Бирюков[1], Л.И.Баранов[1], И.Г.Дибиргаджиев[1], М.В.Шеянов[1], О.А.Касымова[1], О.В.Паринов[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна», ФМБА России, Москва, Россия

**Резюме.** *Цель исследования* – разработка и применение математической модели оценки рисков заражения медицинского персонала, участвующего в оказании медицинской помощи пациентам с COVID-19 в условиях «красной зоны».

*Материалы и методы исследования.* На основании анализа информативных признаков и информации об условиях труда в инфекционном отделении Федерального медицинского биофизического центра им. А.И.Бурназяна ФМБА России разработана система поддержки принятия решений, позволяющая дать объективную оценку рисков заражения медицинского персонала при оказании медицинской помощи в условиях «красной зоны».

*Результаты исследования и их анализ.* Проанализировано влияние различных факторов риска заражения медицинского персонала, участвующего в оказании медицинской помощи пациентам с новой коронавирусной инфекцией COVID-19; определены самые значимые факторы риска.

**Ключевые слова:** доза-эффект, «красная зона», математическая модель оценки рисков заражения, медицинский персонал, новая коронавирусная инфекция COVID-19, пациенты

**Конфликт интересов.** Авторы статьи подтверждают отсутствие конфликта интересов

**Для цитирования:** Анненкова Е.А., Тихонова О.А., Бирюков А.П., Баранов Л.И., Дибиргаджиев И.Г., Шеянов М.В., Касымова О.А., Паринов О.В. Риск-ориентированная модель причинно-следственных связей факторов риска заражения медицинского персонала, участвующего в оказании медицинской помощи пациентам с новой коронавирусной инфекцией COVID-19// Медицина катастроф. 2021. №3. С. 65-68. https://doi.org/10.33266/2070-1004-2021-3-65-68

***Contact information:***
***Elena A. Annenkova –*** Cand. Sci. (Phys.–Math.); Senior Research
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7(499)190-94-35
**E-mail:** a-a-annenkova@yandex.ru

***Контактная информация:***
***Анненкова Елена Александровна –*** кандидат физико-математических наук; старший научный сотрудник
**Адрес:** Россия, 123098, Москва, ул. Живописная, д. 46
**Тел.:** +7(499)190-94-35
**E-mail:** a-a-annenkova@yandex.ru

## Introduction

Emergencies, including epidemics, have a major impact on health care systems. They reveal profound structural and functional problems in the organization of care for the sick and affected. The COVID-19 pandemic illustrates this at the global level. Particular attention in this situation should be paid to the socio-professional group of medical professionals. Because their qualified and coordinated actions primarily affect public health and the health of an individual [1]. The risk of occupational infection leads to disruption of the continuity of medical services. This occurs because it is necessary to establish mandatory quarantine for infected professionals and to suspend them from work. In addition, there is the problem of replacing those who are sick in the workplace. Currently, the COVID-19 pandemic makes it relevant to predict the incidence of disease in health care workers on the basis of data on other viruses from the coronavirus group.

**The aim of the study** is to develop and apply a mathematical model for assessing the risks of infection for the staff involved in providing medical care to patients with COVID-19 in "red zone" conditions.

**Materials and methods of research.** In order to mathematically model the risk of infection of medical personnel in the "red zone" we analyzed the factors influencing the work with COVID-19 patients. The basis for the formation of the space of informative attributes for the mathematical model was the data on the working conditions in the infectious disease department of the State Research Center — A.I. Burnazyan Federal Medical Biophysical Center of the Federal Biomedical Agency of Russia (A.I. Burnazyan Federal Biophysical Center). There, 223 people were involved to provide care for patients infected with SARS-CoV-2. (medical workers, drivers, disinfectors, cooks, workers, etc.), of which 166 people (medical personnel) worked in conditions of high risk of occupational contamination. The medical personnel group included 48 male and 118 female patients aged 18-69 years, mean age (48.7±1.8), of whom 57 were doctors of various specializations and 109 were nurses and auxiliary nurses. None of the study participants had previously worked in an infectious disease department setting and had no special knowledge of virology. Prior to working in the "red zone," all employees were trained in the use of personal protective equipment within a short time frame within a single-type program. They were also informed about the routes of transmission and clinical manifestations of the virus. All individuals in this group had a negative polymerase chain reaction result for SARS-CoV-2 oropharyngeal smear at the time of starting work in the infection department.

The development of a risk-based causal model of risk factors for infection among the staff involved in the care of patients with the new coronavirus infection COVID-19 was carried out in order to develop a response plan for the risk of infection among the staff. A quantitative infection risk assessment method was used. The sensitivity of model parameters was assessed to determine what additional data or knowledge could potentially reduce uncertainty and improve our understanding of the risks under investigation.

After identifying the possible risks of infection by COVID-19 virus among healthcare workers, the following were found to have the greatest impact on the probability of risks: the concentration of the virus in saliva; the concentration of viral particles released into the air by one patient cough and the number of coughs per hour; the frequency of air exchange; the number of room visits by a healthcare worker per hour; the number of patients a healthcare worker came in contact with per room visit; the time taken for each room visit and number of working hours per day (Table 1).

When building a mathematical model, we used the standards of GOST R ISO 7708-2006 ("Air Quality").

The working space of the hospital rooms was also taken into account. Most of the rooms were designed for 4 patients; the volume of the room for 4 patients was 70 m3. Symptomatic patients were considered the only source of infection in the room, with the assumption that COVID-19 is transmitted mainly through aerosols.

Viral release into the room was calculated using the formula:

$$V_i = \frac{\pi d_i^2}{6} \times 10^{-12}, \quad (1)$$

where $V_i$ is the volume of droplets that are ejected into the room during each coughing event; $d_i$ – droplet diameter — assuming its spherical shape [2].

The rate of ventilation flow $q_{vent}$ was determined by the number of air changes per hour per room volume, i.e., by the multiplicity of air changes performed in the rooms of the "red zone" according to the norms for the rooms of infectious patients:

$$q_{vent} = V \times ACH \quad (2)$$

The daily exposure dose in PFU (plaque-forming units) for medical personnel during a room visit with patients with new COVID-19 coronavirus infection was calculated according to the formula:

$$D = C_{CoV} \times C_{saliva} \times N_{cough} \times \frac{1}{q_{vent}} \times \times V_{inhaled} \times N_{room} \times N_{pat} \times t_{spent} \times t_{work} \quad (3)$$

where $C_{CoV}$ – is the concentration of infection in saliva, the average value and distribution of which was calculated based on studies in work [3]; $C_{saliva}$ – the concentration of particles in the air after one cough, which was calculated based on the particle transport model [2]; $N_{cough}$ – number of coughs per hour, whose value range was calculated based on the particle expulsion model from the airways [4]; $V_{inhaled}$ – the air intake rate of the exposed person, equal to the human respiratory rate of 0,5 $m^3/h$ [5]; $N_{room}$ – number of visits to a room by a health care worker per hour; $N_{pat}$ – number of patients with whom the health care worker came into contact per room visit; $t_{spent}$ – time spent on each visit; $t_{work}$ – кnumber of working hours per day – $N_{room}$, $N_{pat}$, $t_{spent}$, $t_{work}$ varied depending on the job functions of health care workers. For example, nurses, on average, went around 6 wards in 1 hour, staying in each ward for 10 minutes. Their working day was 8 hours.

The formula for determining daily exposure dose (3) while wearing a mask is supplemented with the multiplier

$$p_{mask} = \frac{C_{saliva\,in}}{C_{saliva}}$$

where $P_{mask}$ – penetration of particles through the mask, $C_{saliva\,in}$ – concentration of particles that have passed through the mask. In the "red zone" of the infection department at the A.I. Burnazyan Federal Biomedical Center, respirators with FFP3 protection were used, with a filtration efficiency of 99%, i.e. $P_{mask}$≈1 [6]. However, if the mask was not replaced before its efficiency was lost (up to 4 h), one must consider that the particle penetration rate through the mask becomes 100% for the entire time the mask has been worn since the loss of efficiency.

The recommended dose-effect model follows an exponential dose-effect relationship:

$$P_{inf} = 1 - e^{-kD} \quad (4)$$

where $P_{inf}$ – probability (risk) of infection; $k$ – optimized parameter of the dose-effect function, $PFU^{-1}$.

The cumulative risk of morbidity over several days of exposure was modeled as follows:

$$P_M = 1 - \left(1 - P_{inf}\right)^n \quad (5)$$

where $P_M$– probability of incidence; n – number of days of exposure with the probability of infection $P_{inf}$ from daily exposure [7].

**Results of the study and their analysis.** A total of 26 cases (15.6%) of acute occupational COVID-19 disease confirmed by PCR or serological test were recorded during the period of the infectious disease department work. The group of those who fell ill while on duty included 10 nurses, including those working in the anesthesiology department, 9 nurse attendants, and 3 housekeepers (all female). Doctors were less exposed to occupational contamination – 4 cases (two men, two women). The average age of all the patients was (39.63±1.2) years.

All cases were locally acquired in the period from day 8 to day 21 from the opening of the infection department — during the period of learning new skills and gaining experience with this type of infection, because the experience of the staff in the new environment was insufficient.

The empirical value of the probability of infection of the personnel in the "red zone" of the infectious department of the A.I. Burnazyan Federal Medical and Biological Center during one working day with the above clinical data is $P_{inf*} \approx$ 0,0111876. The objective conditions of personnel work in the "red zone" in which such probability of disease became a reality are reflected in the value of parameter $D$ calculated according to formula (3). On the basis of the calculated values of $P_{inf*}$ and $D$ we obtain an empirical estimate of the $k$ parameter value by the formula:

$$k = -\frac{\ln(1 - P^*_{inf})}{D} \quad (6)$$

The value obtained is $k$ = 13,8238987774. Thus, knowing the optimized parameter of the dose-effect function $k$ and applying formula (5), we can estimate the risks of infection for medical personnel involved in providing medical care to patients with new coronavirus infection COVID-19, taking into account their working conditions — size and ventilation of rooms, number of patients per ward, ward visit regime, working day duration, and provision of personal protective equipment (Table 2). A comparative analysis of infection risks under different conditions revealed that the absence of personal protective equipment or its untimely replacement had the greatest influence on the risk increase — under these circumstances, the risk increased 17-fold.

The practical significance of the study is determined by its focus on improving the organizational foundations of hygienic assessment of working conditions, which will help to identify the harmful industrial effects of the new coronavirus infection COVID-19 and to develop measures to eliminate them. Of practical interest are the proposals made to preserve and improve the health of medical workers, increase their awareness of health risk factors in the conditions of "covid hospital".

*Таблица 1/Table No. 1*

**Параметры модели**

Model parameters

| | | |
|---|---|---|
| 1 | ***D*** | Суточная доза воздействия в PFU (бляшкообразующие единицы) для медсестер и других медицинских работников /Daily exposure dose in PFU (plaque units) for nurses and health care workers |
| 2 | $C_{CoV}$ | Концентрация инфекции в слюне, PFU/мл Infection concentration in saliva, PFU/ml |
| 3 | $C_{saliva}$ | Концентрация частиц в воздухе после одного кашля, 1/м$^3$ / Concentration of particles in the air after one cough, 1/m$^3$ |
| 4 | $N_{cough}$ | Количество кашлей в 1 ч / Number of coughs in 1 h |
| 5 | $q_{vent}$ | Расход вентиляционного воздуха в помещении, м$^3$/ч / Ventilation air flow rate in the room, m$^3$/h |
| 6 | $V_{inhaled}$ | Скорость забора воздуха человеком, подвергшимся воздействию, м$^3$/ч Rate of air intake by an exposed person, m$^3$/h |
| 7 | $N_{room}$ | Количество посещений палаты медсестрой или другим медицинским работником в 1 ч Number of visits to the room by a nurse or a health care worker in 1 hour |
| 8 | $N_{pat}$ | Число пациентов, с которыми контактировала(л) медсестра или другой медицинский работник за одно посещение палаты Number of patients visited by a nurse or a health care worker per room visit |
| 9 | $t_{spent}$ | Время, затраченное на каждое посещение, ч Time spent on each visit, h |
| 10 | $t_{work}$ | Количество рабочих часов в сутки Number of working hours per day |
| 11 | $P_{inf}$ | Вероятность (риск) заражения персонала в течение одного рабочего дня /Probability (risk) of infection of personnel within one working day |
| 12 | ***k*** | Оптимизированный параметр функции доза-эффект, PFU$^{-1}$ Optimized dose-effect function parameter, PFU$^{-1}$ |
| 13 | $P_m$ | Кумулятивная вероятность заражения в течение n рабочих дней /Cumulative probability of infection within n working days |
| 14 | ***n*** | Количество дней воздействий с $P_m$ вероятностью заражения от ежедневного воздействия Number of days of exposure with $P_m$ probability of infection from daily exposure |

*Таблица 2 / Table No. 2*

**Прогнозируемые значения заболеваемости медперсонала в «красной зоне» инфекционного отделения ФМБЦ им. А.И. Бурназяна ФМБА России**

Predicted values for staff morbidity in the "red zone" of the infectious diseases department of the A.I. Burnazyan Federal Medical and Biological Center of the Federal Medical and Biological Agency of Russia

| День (сутки) Day (24 hours) | Значение риска – кумулятивный риск заражения в течение нескольких дней, Pm Risk value – cumulative risk of infection over several days, Pm | Общее число сотрудников, чел. Total number of employees, people | Прогноз доли заболевших от общего числа сотрудников, % Forecast of the share of sick people in the total number of employees, % |
|---|---|---|---|
| 1-й / 1st | 0,0111876000 | 166 | 1,9 |
| 2-й / 2nd | 0,0222500376 | 166 | 3,7 |
| 3-й / 3rd | 0,0331887131 | 166 | 5,5 |
| 4-й / 4th | 0,0440050111 | 166 | 7,3 |
| 5-й / 5th | 0,0547003006 | 166 | 9,1 |
| 6-й / 6th | 0,0652759355 | 166 | 10,8 |
| 7-й / 7th | 0,0757332545 | 166 | 12,6 |
| 8-й/ 8th | 0,0860735811 | 166 | 14,3 |
| 9-й / 9th | 0,0962982243 | 166 | 16,0 |
| 10-й /10th | 0,1064084783 | 166 | 17,7 |
| 11-й /11th | 0,1164056228 | 166 | 19,3 |
| 12-й /12th | 0,1262909233 | 166 | 21,0 |
| 13-й /13th | 0,1360656310 | 166 | 22,6 |
| 14-й /14th | 0,1457309831 | 166 | 24,2 |

The developed recommendations on the use of the algorithm of risk assessment for medical staff in the presence of infectious agents with airborne transmission mechanism in the working environment are aimed at reducing the health risk in this professional group. They can be used in the practical work of hygienists, hospital epidemiologists, health care organizers, and occupational safety engineers of medical treatment organizations.

**Conclusion**

This work was carried out under conditions of constantly changing baseline data. This is due both to the novelty of the problem under study and, accordingly, to the ever-increasing number of observations and the large number of studies on the subject, which, in turn, leads to constantly refined conclusions. In such a situation, a risk-oriented model was chosen, which corresponds to the global trends [8-11].

Our study confirmed that in order to reduce the risks of infection of medical personnel with the new COVID-19 coronavirus infection, it is necessary to educate the staff of medical treatment organizations on the strict observance of all safety measures when working with infectious patients. To raise the awareness of medical workers, it is necessary to include reports on the main health risk factors in the programs of industry and city medical conferences, taking into account regional peculiarities of the incidence of the new COVID-19 coronavirus infection.

The theoretical significance of the work performed consists in the fact that a mathematical model to estimate the risks of infection of medical personnel in specific conditions of work with infectious patients based on the quantification of key factors on which the "efficiency" of person-to-person transmission of an infectious agent depends was obtained and tested. The established correlations between the possibility of infecting medical workers and occupational factors are a subject for further research. They can be used in the development of comprehensive health care programs for medical personnel involved in the provision of medical care to patients with the new coronavirus infection COVID-19.


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*Review article*


# PROBLEMS OF DEVELOPMENT AND IMPLEMENTATION OF PERSONAL PROTECTION EQUIPMENT FOR PERSONNEL OF RADIATION AND CHEMICAL HAZARDOUS FACILITIES, EMERGENCY AND RESCUE TEAMS AND POPULATION

V.I.Rubtsov[1], G.A.Novikov[1], A.N.Timoshenko[1], G.P.Prostakishin[1]

[1] State Research Center – Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, Moscow, Russian Federation

**Abstract.** The article presents a brief review of the activities of the laboratory "Personal protection equipment for the personnel of hazardous production facilities" for creation of the regulatory-legal and regulatory-methodological support system for personal protection of the personnel of radiation and chemical hazardous facilities, of regular and non-staff emergency rescue teams of Rosatom State Corporation and of FMBA of Russia as well as of the population living in the influence area of the mentioned facilities.
The issues of standardization and certification of personal protective equipment at NPPs and in the field of atomic energy use — both in the normal operation mode of dangerous objects, and in emergency situations of peace and war time are considered.
The problems arising in the implementation of innovative personal protective equipment, primarily due to international obligations, are shown.
**Key words:** *ccertification, emergency rescue teams, emergencies, personnel, population, personal protective equipment, radiation and chemical hazardous production (objects), sanitary and epidemiological standardization, standardization, technical regulation*

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*Обзорная статья*


# ПРОБЛЕМЫ РАЗРАБОТКИ И ВНЕДРЕНИЯ СРЕДСТВ ИНДИВИДУАЛЬНОЙ ЗАЩИТЫ ПЕРСОНАЛА РАДИАЦИОННО- И ХИМИЧЕСКИ ОПАСНЫХ ОБЪЕКТОВ, АВАРИЙНО-СПАСАТЕЛЬНЫХ ФОРМИРОВАНИЙ И НАСЕЛЕНИЯ

В.И.Рубцов[1],Г.А.Новиков[1], А.Н.Тимошенко[1], Г.П.Простакишин[1]

[1] ФГБУ «ГНЦ – Федеральный медицинский биофизический центр им. А.И.Бурназяна» ФМБА России, Москва, Россия

**Резюме.** Представлен краткий обзор деятельности лаборатории «Средства индивидуальной защиты персонала опасных производств» по созданию системы нормативно-правового и нормативно-методического обеспечения индивидуальной защиты персонала радиационно- и химически опасных объектов, штатных и нештатных аварийно-спасательных формирований Госкорпорации «Росатом» и ФМБА России, а также населения, проживающего в зоне влияния указанных объектов.
Рассмотрены вопросы стандартизации и сертификации средств индивидуальной защиты (СИЗ) на АЭС и в области использования атомной энергии – как при штатном режиме функционирования опасных объектов, так и в условиях чрезвычайных ситуаций (ЧС) мирного и военного времени.
Показаны проблемы, возникающие при внедрении новых инновационных СИЗ, обусловленные, прежде всего, международными обязательствами.

**Ключевые слова:** *аварийно-спасательные формирования, население, персонал, радиационно- и химически опасные производства (объекты), санитарно-эпидемиологическое нормирование, сертификация, средства индивидуальной защиты, стандартизация, техническое регулирование, чрезвычайные ситуации*

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***Contact information:***
***Viktor I. Rubtsov –*** Dr. Sc. (Techn.), Candi. Sc. (Chem.); Head of the Laboratory of Personal Protective Equipment of the Industrial Radiation Hygiene Department
**Address:** 46, Zhyvopisnaya str., Moscow, 123098, Russia
**Phone:** +7 (499) 190-96-91
**E-mail:** siz-fmbc@mail.ru

***Контактная информация:***
***Рубцов Виктор Иванович*** – доктор технических наук, кандидат химических наук; заведующий лабораторией средств индивидуальной защиты отдела промышленной радиационной гигиены
**Адрес:** Россия, 123098, г. Москва, ул. Живописная, д. 46
**Тел.:** +7 (499) 190-96-91
**E-mail:** siz-fmbc@mail.ru

The Laboratory of Personal Protective Equipment at the A.I. Burnazyan Federal Medical and Biophysical Center was established in 1953 as an independent scientific unit. Before that the work in this direction was carried out by a special group created in 1948 in the structure of the Institute of Occupational Hygiene and Occupational Diseases [1]. In the mid-1950s the intensive work of the laboratory gave great results [2]. Such inventions as light high-efficiency respirators ShB-1 "Lepestok-200", additional film overalls and special footwear, hose-type means of individual respiratory protection, pneumatic suits etc. were created and are still in use today. [3]. Technical characteristics of the used materials and means of individual protection in were published in the USSR the first detailed Catalogue. They can also be seen in the regularly published since 2003 Directory-Catalogue. Its latest edition was published in 2020. [2-5] — Figure.

The laboratory was engaged in the development of personal protective equipment until the 1990s. At that time it had its own large experimental production and more than 500 employees worked there.

Specialists of the laboratory have developed the Standard Table of Equipment for Emergency Rescue Units of Rosatom with Personal Protective Equipment, as well as several documents for different divisions of the State Corporation, which establish Standard Norms for issuing certified personal protective equipment[6].

It should be noted that the laboratory staff has always paid great attention not only to the development of individual protection means, but also to normative-methodological and normative-legal documents on individual protection. So, one of the first standards on means of individual protection which is still in force is GOST 12.4.028-76 [7]. Since that time more than 100 standards for personal protective equipment and methods of their testing have been developed at the Burnazyan Federal Medical and Biological Center. At present, the Center has the PK-1 "Insulating Suits" TK-320 "Personal Protective Equipment". Laboratory staff developed more than 10 SanPiN, which set the requirements for personal protective equipment, including SanPiN 2.2.8.46-03 "Sanitary rules for decontamination of personal protective equipment"; SanPiN 2.2.8.47-03 "Insulating suits for protection against radiation and chemical toxic substances"; SanPiN 2.32.8.48-03 "Personal respiratory protective equipment for personnel at radioactively hazardous production facilities"; SanPiN 2.2.8.49-03 "Personal skin protective equipment for personnel at hazardous production facilities", which were registered with the Russian Ministry of Justice and effective since January 1, 2021.

The laboratory experts as members of the working groups for the development of the first rules for the certification of personal protective equipment participated in the preparation of the following documents: "Unified sanitary-epidemiological and hygienic requirements for goods subject to sanitary and epidemiological supervision (control)". Requirements approved by the Decision of the Customs Union Commission of 28.05.2010 № 299; Technical Regulations TR CU 019/2011 "On the safety of personal protective equipment".

On the basis of the laboratory the Test Center "Individual Protection", accredited by Rosatom State Corporation for certification testing of all personal protective equipment used at the radiation and chemical facilities of Rosatom operates.

At present the accreditation of the Body for Conformity Assessment (Mandatory Certification) of Personal Protective Equipment in the field of the use of atomic energy is being completed. In general, the laboratory has been engaged in certification of personal protective equipment since 1993, when it was first accredited by Rosstandart.

It must be said that certification of personal protective equipment is currently associated with great difficulties. It is connected with rapid changes in the normative base and transition of the Russian Federation to new American and European standards. In addition, the transition to new methods, which can be implemented only on imported expensive equipment included in the State Register, requires large material and time expenditures. The center must purchase equipment, materials, reagents and services for equipment verification on a competitive basis (the total range of purchased products and services is many thousands of items). And this is a very complicated process. It can be simplified by making a simple decision. If a bona fide supplier produces products with stable technology that meets the established requirements, and has been doing so from the same type of

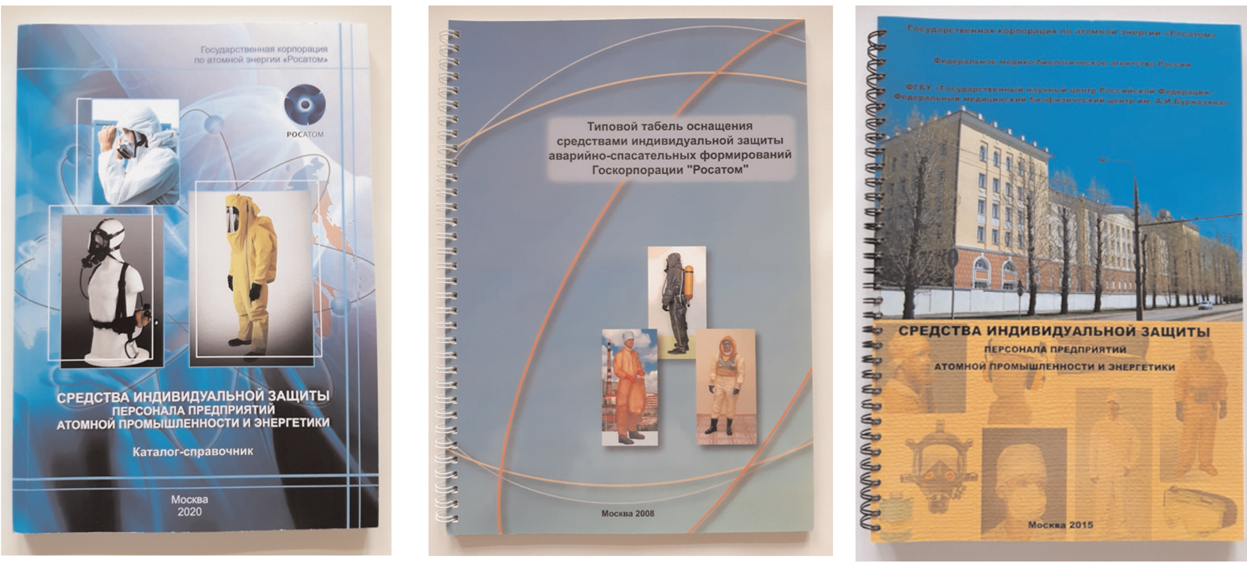


**Рисунок**. Нормативно-методические и нормативно-правовые документы по средствам индивидуальной защиты человека
**Figure**. Regulatory and methodological documents on personal protective equipment

raw materials for many years, why do they have to go through lengthy procedures? Especially since they are often conducted by "specialists" who have been trained in new specialties, particularly in "conformity assessment." They do not have any work experience and do not know not only the specifics of real production of personal protective equipment, but also the specifics of its application in conditions of radiation and chemical hazardous production in peacetime and wartime. If there are 25 or 18 technical regulations in the accreditation area of the certification body or testing center, the certificates and protocols issued by them are questionable.

For many years we have been engaged in training and certification of professional rescuers, specialists of regular and non-staff emergency rescue services and formations of ROSATOM. We have been working since their formation at the Central Industry Commission for Attestation of Emergency Rescue Services, Emergency Rescue Units and Rescuers — COAK-1 (State Corporation) and the Industry Attestation Commission — UAC-3 (TVEL). And we can see how long, time-consuming and financially expensive the process of formation of such high-class specialists as production managers and rescuers of the nuclear industry is.

It should be noted that in the system of Rosatom and FMBA of Russia, over the many years that have passed since the Chernobyl accident, this process has been fine-tuned to the smallest detail and is functioning normally. The same cannot be said of the conformity assessment processes. Their rules are very complicated and, unfortunately, change frequently. This happens without taking into account the opinions of professionals who conduct real tests, not purely computer simulations. If you create test centers "in the open field", it will require very large capital investments. And this process will end in the absence of experienced professional staff capable of operating complex imported equipment. Maybe that's why we have to deal with certificates issued on the basis of protocols that do not confirm the real protective characteristics of personal protective equipment, which will be required from the products in the conditions of their use. The fact that business is now really leading the rulemaking and conformity assessment processes is a dangerous trend. For business, it's all about making a profit, not ensuring safety. Under the Labor Code, safety is the employer's responsibility. At the same time the employer has no opportunity to fully verify the characteristics of the personal protective equipment supplied. Very often during certification one product is provided for testing, but a cheaper "analogue" is supplied. In Europe and the USA, testing centers are usually part of large multinational corporations. These corporations can afford to incur large expenses on science. But in our country, it is forbidden by law — a test center must be independent. In addition, they also value long-standing suppliers, while we are offered to change them on a competitive basis all the time.

In general, in the nuclear industry the problem of providing certified personal protective equipment to the personnel of the main production facilities, emergency services and formations is solved at a rather high level. But there are individual cases of delivery of counterfeit and counterfeit products, as well as deliveries of personal protective equipment with almost expired warranty shelf life. It is more difficult to provide the population with personal protective equipment, which is regulated by Order No. 543 of the Ministry of Emergency Situations of Russia dated October 1, 2014, as amended by Order No. m309 of the Ministry of Emergency Situations of Russia dated 31.07.2017 and GOST R 22.9.14-2014 "BCHS. Personal protective equipment in emergencies. Gas-dust-proof respirators. RESPIRATORS."; GOST R 22.9.19-2014 "BCHS. Personal protective equipment for respiratory system in emergencies. Filtering gas masks. OTT"; GOST R 22.9.02-2014 "BCHS. Means of Personal Respiratory System Protection in Emergency Situations. Filtering gas masks and self-rescuers. Test methods".

According to item 2 of the mentioned order "Provision of the population with means of individual protection is carried out ... from dangers arising in the course of military conflicts or as a result of such conflicts, as well as for protection of the population in emergencies. Personal protective equipment for the population includes means of individual protection of respiratory organs and medical means of individual protection". It is noteworthy that the order does not mention means of personal skin protection, while many hazardous chemicals, penetrating through the skin, can cause fatal poisoning.

Clause 6 of the Order stipulates that "the population residing and/or working in areas within the boundaries of the zone ... of possible radioactive and chemical contamination established around radiation, nuclear and chemical hazardous facilities shall be provided with personal protective equipment" — contamination zones are not necessarily adjacent to the facility. They can be at a considerable distance from it, for example, where precipitation has fallen, etc. Unfortunately, now four federal agencies cannot agree on the names and criteria for defining zones. It is not clear from point 9 of the order, who is entitled to what respirators and who is entitled to medical personal protective equipment. According to GOST R 58396-2019 and GOST PNST 4285-2020, medical masks are not personal protective equipment. Any requirements for personal protective equipment are not established in the order of EMERCOM of Russia, but it is stated that "after the expiration date based on the results of laboratory tests (inspections) issued by laboratories and other authorized organizations, the storage period is extended or personal protective equipment is written off". In this case the tests are carried out on all indicators — p.17, 18. However, in GOST R 22.9.14-2014 ... there are no sections on acceptance rules and test methods. In addition, it is not clear whether any accreditation is needed, for example, when testing for iodine-131 and methyl iodide, and how the resistance to storage of rubber parts of respirator construction is tested. There is also a question: Clause 1 states that the standard applies to gas-dust-proof respirators intended for use against biological contamination, while Clause 2 establishes that it does not apply to "medical" respiratory protection equipment.

GOST R 22.9.19-2014 formulates requirements for civilian filtering gas masks, including protection from radioactive iodine-131 and methyl iodide. And GOST R 22.9.20-2014 defines methods of testing gas masks and filtering self-rescuers in emergencies. There is also a reference that these indicators are determined by GOST 12.4.217-2001. However, this GOST does not contain a description of this method. At the same time there is STO 95 12035-2018 "Personal respiratory protective equipment. Requirements for the method of measuring the protection factor of filtering materials (filters) in relation to radioactive iodine and its compounds.

Clause 1.3 of the Technical Regulations of the Customs Union 019/2011 "On the safety of personal protective equipment" states that it applies to personal protective equipment against the listed factors, including the effects of biological factors (microorganisms, insects). At the same time in the text of the regulation there are very few requirements for personal protective equipment against microorganisms.

In the GOST of the system of safety in emergency situations it is also often mentioned that personal protective equipment protects against biological factors, but in fact there are no requirements for it. There are also no requirements for the hygienic characteristics of the materials and even less for their effect on the protective properties.

In 2020, during the COVID-19 pandemic, conducting studies of protective coveralls widely used worldwide for protection against a new coronavirus infection, we confirmed the conclusion of American colleagues: materials with low air and vapor permeability poorly remove sweat from the undergarment space and promote penetration of hazardous substances into the undergarment space [8, 9]. This fact testifies to the necessity of expanding research on the whole complex of protective and hygienic properties of materials and products protecting against the impact of radiation, chemical and biological factors.

**Conclusion**

This brief review shows the need for a comprehensive systematic approach to ensuring the safety of rescuers, personnel of radiation, chemical and biological hazardous industries and the population living in areas of their impact. This concerns both standard operation and peacetime and wartime emergencies, as well as the possible combined effects of various factors. It should also be taken into account that about 40% of accidents are accompanied by a fire. And all of them are connected with huge psycho-emotional loads, which are aggravated by the very fact of use of personal protective equipment, which reduce working capacity of a person and require regulation of work and rest regimes.

The system of standardization, selection, quality control, conformity assessment, decontamination and disposal of personal protective equipment, training and certification of personnel of radiation and chemical hazardous industries and emergency rescue teams established in ROSATOM allows the largest enterprises of the nuclear industry to avoid serious accidents and keep occupational disease rate at a low level.

At present, many problems of development of new personal protective equipment and its implementation in the nuclear industry are associated with changes in the system of their standardization and certification at the international and interstate levels. As for personal protective equipment, the key problem here is the lack of regulation of their compliance with the requirements of mandatory certification in the EAU — Eurasian Conformity (EAC) and safety in emergency situations or registration.

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***Original article***


# PROSPECTS FOR CREATION OF AUTONOMOUS LIFE SUPPORT COMPLEXES USING BIOLOGICAL SYSTEMS FOR ARCTIC AND FAR NORTH CONDITIONS

I.V.Markin[1], E.S.Shchelkanova[1], R.A.Volodyashkin[1], E.A.Zhurbin[1], A.Ya.Fisun[1]

[1] Military innovative technopolis "ERA", Anapa, Russian Federation

**Abstract.** *The purpose of the study* is a comparative analysis of the implemented projects of closed ecological systems and the creation on their basis of own scheme of autonomous life-support complex for the conditions of the Arctic and the Far North. *Materials and methods of research.* The object of the study is implemented projects of closed ecological systems. The subject of the study is the principles of configuration of such projects, their main components and the relationship between them. *Research results and their analysis.* The support systems created at different times, with the purpose to be used in long-duration space flights or to carry out fundamental ecological research, were analyzed. Such projects were based on the use of biological systems, which opens the possibility of their use to ensure the autonomy of infrastructure in the Arctic and Far North. The scheme of the complex planned for development is proposed. This complex allows to recycle waste products, meets human nutritional needs and produces biofuel of the third generation.

**Key words:** *Arctic and Far North areas, biofuel, BIOSPHERA-2 project, life support systems, MELISSA project, microalgae, project, proposed life support system BIOS project*

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***Оригинальная статья***


# ПЕРСПЕКТИВЫ СОЗДАНИЯ АВТОНОМНЫХ КОМПЛЕКСОВ ЖИЗНЕОБЕСПЕЧЕНИЯ С ИСПОЛЬЗОВАНИЕМ БИОЛОГИЧЕСКИХ СИСТЕМ ДЛЯ УСЛОВИЙ АРКТИКИ И КРАЙНЕГО СЕВЕРА

И.В.Маркин[1], Е.С.Щелканова[1], Р.А.Володяшкин[1], Е.А.Журбин[1], А.Я.Фисун[1]

[1] ФГАУ «Военный инновационный технополис «ЭРА», Анапа, Россия

**Резюме.** *Цель исследования* – сравнительный анализ реализованных проектов замкнутых экологических систем и создание на их основе собственной схемы автономного комплекса жизнеобеспечения для условий Арктики и Крайнего Севера.

*Материалы и методы исследования.* Объект исследования – реализованные проекты замкнутых экологических систем. Предмет исследования – принципы конфигурации подобных проектов, их основные компоненты и взаимосвязь между ними.

*Результаты исследования и их анализ.* Проанализированы созданные в разное время системы жизнеобеспечения, назначением которых являлось использование в длительных космических полетах или проведение фундаментальных экологических исследований. Показано, что подобные проекты были основаны на использовании биологических систем, что говорит о возможности их применения для обеспечения автономности инфраструктуры в районах Арктики и Крайнего Севера. Предложена схема планируемого к разработке комплекса, позволяющего перерабатывать отходы жизнедеятельности, удовлетворять потребности людей в питании, производить биотопливо третьего поколения.

**Ключевые слова:** *биотопливо, микроводоросли, предлагаемый проект системы жизнеобеспечения, проект БИОС, проект БИОСФЕРА-2, проект МЕЛИССА, районы Арктики и Крайнего Севера, системы жизнеобеспечения*

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***Contact information:***
***Elena S. Shchelkanova*** **–** Cand. Sc. (Biol.); Head of the Laboratory for Additive Technologies and Professional Reliability
**Address:** 41, Pionerskiy avenue, Anapa, 353456, Russia
**Phone:** +7 (921) 668-55-27
**E-mail:** shchelkanova_el@mail.ru

***Контактная информация:***
***Щелканова Елена Сергеевна*** **–** кандидат биологических наук; начальник лаборатории аддитивных технологий и профессиональной надежности
**Адрес:** Россия, 353456, Анапа, Пионерский пр-т, 41
**Тел.:** +7(921) 668-55-27
**E-mail:** shchelkanova_el@mail.ru

The Arctic Zone of the Russian Federation (hereinafter — the Arctic Zone, the Arctic) plays a major role in the development of the country: it generates 12-15% of the gross domestic product of Russia, it provides about a quarter of its total exports [1].

The Strategy for the Development of the Arctic Zone of the Russian Federation and Ensuring National Security for the period up to 2035 indicates the reasons for the importance of the Arctic Zone:

- The region's share of natural gas and oil production in the Russian Federation is 80 and 17%, respectively;
- The Arctic zone is a platform for major investment projects and ensures the demand for high-tech products;
- The continental shelf of the Russian Federation in the Arctic is a strategic reserve for the development of Russia's mineral resource base;
- The facilities of the strategic deterrence forces are located in the Arctic zone in order to prevent aggression against the Russian Federation and its allies*.

It should be noted that the Arctic, being a valuable resource and raw material base, is a possible area of conflict of interests of different countries. This leads to the need to establish military bases there and to strengthen the presence of the Armed Forces of the Russian Federation. The military infrastructure of the region serves not only to protect civilian structures, but also as a reference point for their deployment.

The development of the Arctic and the solution of military tasks is associated with certain difficulties [2]. They arise because of its harsh climate, limited transport accessibility, and low population density. Among the main factors are:

- lack of state support for delivery of fuel, food and other vital goods to remote settlements, low level of development of transport infrastructure;
- high share of local power generation based on economically inefficient and environmentally unsafe diesel fuel;
- weak interaction of the research and development sector with the real sector of the economy, openness of the innovation cycle;
- increasing conflict potential in the Arctic, which requires a constant increase in the combat capabilities of groups of troops of the Armed Forces of the Russian Federation, other troops, military formations and bodies in the Arctic zone.

Taking into account the problems outlined above, it can be assumed that biological life support systems could be a promising tool for the development of the Arctic and Far North territories. Such systems can produce food and fuel, provide comfortable living conditions for personnel at military bases, and, as a knowledge-intensive project, contribute to the development of the innovation sector of the economy. The importance of using such technologies in the development of the Arctic is emphasized by many Russian scientists, in particular, by the president of the Kurchatov Institute Research Center M.V. Kovalchuk [3]. Let us consider in more detail their types, characteristics and properties, which are useful for ensuring continuous work of people in the Arctic and Far North zones.

***The purpose of the study i***s a comparative analysis of the implemented projects of closed ecological systems and the creation on their basis of own scheme of autonomous life-support complex for the conditions of the Arctic and the Far North.

***Materials and methods of research.*** The object of the study is implemented projects of closed ecological systems. The subject of the study is the principles of configuration of such projects, their main components and the relationship between them.

***Research results and their analysis.***

General characteristics of life support systems

Life support systems are a set of equipment designed to ensure human survival in a hostile environment. For example, in space, underwater, underground or in desert areas [4].

Autonomous complexes that provide regeneration of vital resources are called closed-loop systems. When they are used, the initial supply of resources is placed in the system, after which there is a continuous process of their regeneration [5].

Depending on the processes underlying closed-loop systems, they are divided into physical-chemical and biological, as well as hybrid ones that include features of the former and the latter. Physical-chemical processes include the use of filters, methods of physical or chemical separation of substances, concentration processes, etc. Biological processes are based on the use of the ability of living organisms such as plants or bacteria to create or to break down various organic molecules. The first life support systems used were based on the use of physicochemical methods. This was due to the high degree of knowledge of such methods, to the small size of the devices, to the possibility of precise control of their work. On the other hand, they require large amounts of expensive energy and are not able to replenish food supplies, which must be delivered from outside. Biological processes are less well understood and more difficult to control. But the main advantages of closed-loop biological systems are: lower energy costs; possibility of recycling carbon dioxide, waste water and regeneration of oxygen and water; obtaining biofuel; possible replenishment of provisions — growing grain and vegetable crops, breeding some livestock and fish species, obtaining food additives, particularly protein and vitamin complexes with a radioprotective effect) [6-9].

Since the 1960s, such properties of these systems have led to increased interest in them on the part of scientists. The largest research works in this area were the projects BIOSPHERA-2, MELiSSA, BIOS-3. Let us carry out a comparative analysis of the structure and functioning features of each of these projects.

*Project BIOSPHERA-2*

The largest artificial ecosystem created to date is the BIOSPHERA-2 project. Its design was aimed at getting as

* On the Strategies of development of the Arctic zone of the Russian Federation and ensuring national security for the period up to 2035: Decree of the President of the Russian Federation of October 26, 2020 No. 645

close as possible to the complex structure and diversity of the Earth's ecosystem. For this purpose, models of many biomes were created, including tropical forest, savannah, ocean, desert. The purpose of the creation of the complex was to provide life support for 8 participants of the experiment for two years [10].

BIOSPHERA-2 contained 7 biomes, 2 of which represented anthropogenic ecosystems (human habitation and agricultural zone); the remaining 5 simulated natural zones: tropical forest, desert, savannah, swamp, and ocean [11].

The preset temperature in each biome was maintained by air conditioning systems installed in the basement of the complex. The ventilation system allowed controlling the flow of conditioned air back to the complex, depending on the simulated time of day or season [12].

The oxygen content in the atmosphere of BIOSPHERA-2 decreased during two years of the experiment. Studies have shown that some of the oxygen in the form of $CO_2$ molecules was absorbed by the concrete used in the construction of the complex, by sea water and by loose carbonate soils [13].

Soil reactor technology was used for air purification instead of traditional energy- and resource-consuming filtration and catalytic oxidation methods. The air was blown through a soil layer in which an active microbial community functioned to purify it from various gases, including CO, $H_2S$, $SO_2$, $NH_3$, etc. [13].

A complete hydrological cycle functioned in the complex. Water vapor was released into the atmosphere by evaporation from the surface of the soil and ocean, as well as by transpiration of plants. The condensate formed on the cooling coils of the air conditioners was collected in the troughs. From the troughs it was pumped into storage tanks. After collection, condensed water was distributed for the needs of the complex. Waste generated by humans and farm animals was treated with the participation of microbial and plant communities [10].

The BIOSPHERA-2 agricultural biome included beds for cultivating plants, several flooded areas for growing fish and rice, an orchard, and containers located on the balcony and in the basement. Disease- and pest-resistant plant varieties were pre-selected for use in BIOSPHERA-2. A total of 86 varieties of crops grew in the complex.

BIOSPHERA-2 was the first project that used farm animals and birds — goats, pigs, chickens. They fed on parts of plants that are inedible to humans. They performed several functions in a complex: they gave milk, eggs and meat, which served as an important component of the staff's diet, and they also took part in the cycle of substances, consuming inedible plant residues [13].

*MELiSSA Project*

The purpose of the Melissa project (Micro-Ecological Life Support System Alternative) is to study the mechanisms of functioning of regenerative life support systems for their application in long-term space missions. The concept of the project was first developed by Professor Mergeay in 1987 and has remained virtually unchanged since then [14].

The idea of the project is based on duplicating the functions of the Earth's biosphere without using the reserves of its resources. In contrast to the BIOSPHERA-2 project, the MELiSSA project does not create miniature copies of biomes already existing in nature. On the contrary, its biosphere is so reduced that it is only capable of carrying out the basic biological processes that support global ecological functions. MELiSSA consists of 5 compartments connected to each other and forming a single closed regenerative system — Fig. 1 [14].

In the first compartment, which is an anaerobic thermophilic bioreactor, decomposition of biological waste such as inedible plant parts, personnel waste, etc. takes place. The microbial community in this reactor is quite diverse. It includes various anaerobic thermophilic bacteria and microbiota contained in fecal matter.

The products of anaerobic fermentation are volatile fatty acids, mineral salts and ammonium, which are sent to the second compartment. There, under the influence of sunlight, photoheterotrophic bacteria Rhodospirillum rubrum decompose volatile fatty acids into carbon dioxide. After that, the obtained substances enter the third compartment.

The third compartment is an aerobic bioreactor in which nitrifying bacteria of the genera Nitrosomonas and Nitrobacter immobilized on special beads are co-cultivated. It is designed to convert ammonium nitrogen into the oxidized form of nitrate, because in this form it can be assimilated by higher plants and cyanobacteria.

The fourth compartment consists of two parts. The first part contains a photobioreactor with a culture of the photoautotrophic cyanobacterium Arthrospira platensis, intended mainly for oxygen regeneration and $CO_2$ absorption. In the second part, several cultures of higher plants (wheat, lettuce, beets) are grown, which are a source of nutrition and participate in oxygen enrichment of the air. In addition, the higher plants are able to regenerate drinking water by transpiration.

Finally, the fifth compartment represents the staff of the complex itself, whose basic needs are provided by the other components of the system. Currently, this role is played by laboratory animals.

*BIOS Project*

The first attempt to create a bioregenerative life support system was made in the 1960s in the USSR at the Institute of Biophysics of the Russian Academy of Sciences in Krasnoyarsk. The goal of the project was to create a closed system that would allow to simulate Earth conditions during long-lasting space flights for a long time. BIOS-1 was a system of two connected chambers. The first one — with a volume of 12 m$^3$ — was designed for human habitation. The second one contained an 18-liter photobioreactor in which Chlorella vulgaris microalgae were cultivated [15].

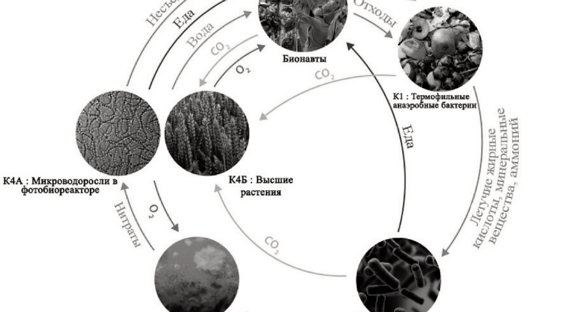


**Рис. 1.** Схема функционирования и взаимосвязи отдельных компартментов системы MELiSSA

**Fig. 1.** Scheme of functioning and interconnection of individual compartments of MELiSSA system

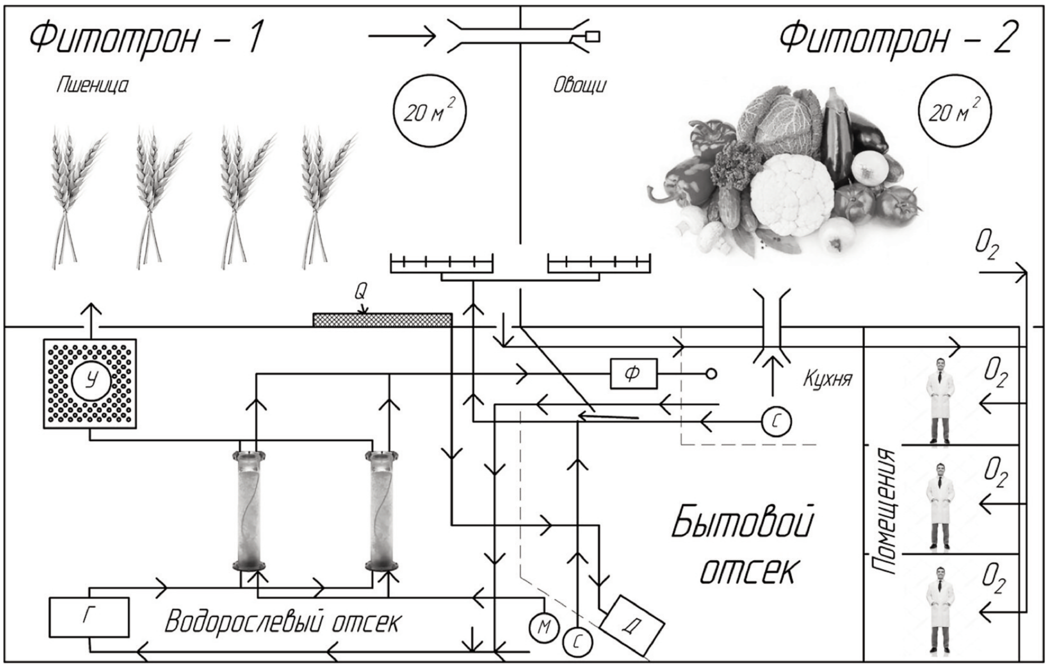


**Рис. 2.** Схема проекта БИОС-3: В - фотобиореактор, Г – газодувка, У – угольный фильтр, С – сборники сточной воды, Q – коллектор конденсата влаги, Д – емкость для кипячения и хранения питьевой воды, М – коллектор мочи, Ф – узел доочистки питьевой воды

**Fig. 2.** Schematic diagram of the project BIOS-3: C – photobioreactor, D – gas blower, U – carbon filter, C – waste water collectors, Q – moisture condensate collector, E – potable water boiling and storage tank, M – urine collector, F – potable water additional treatment unit

By conducting a series of 7 experiments, the scientists managed to achieve complete air closure of the system and 80-85% water closure. In addition, they managed to provide up to 20% of the daily human food [17]. In 1968, it was decided to attach an additional module to the BIOS-1, the so-called phytotron. It was intended for growing higher plants; the created unit was called BIOS-2.

In 1972, a fundamentally new artificial ecosystem — BIOS-3 (Fig. 2) was created. The hermetic construction was divided into 4 compartments. The first one was designed for the accommodation of 3 personnel and included sleeping quarters, a toilet, a kitchen, a control room and a working area. The second compartment contained a photobioreactor with microalgae which provided sufficient air regeneration

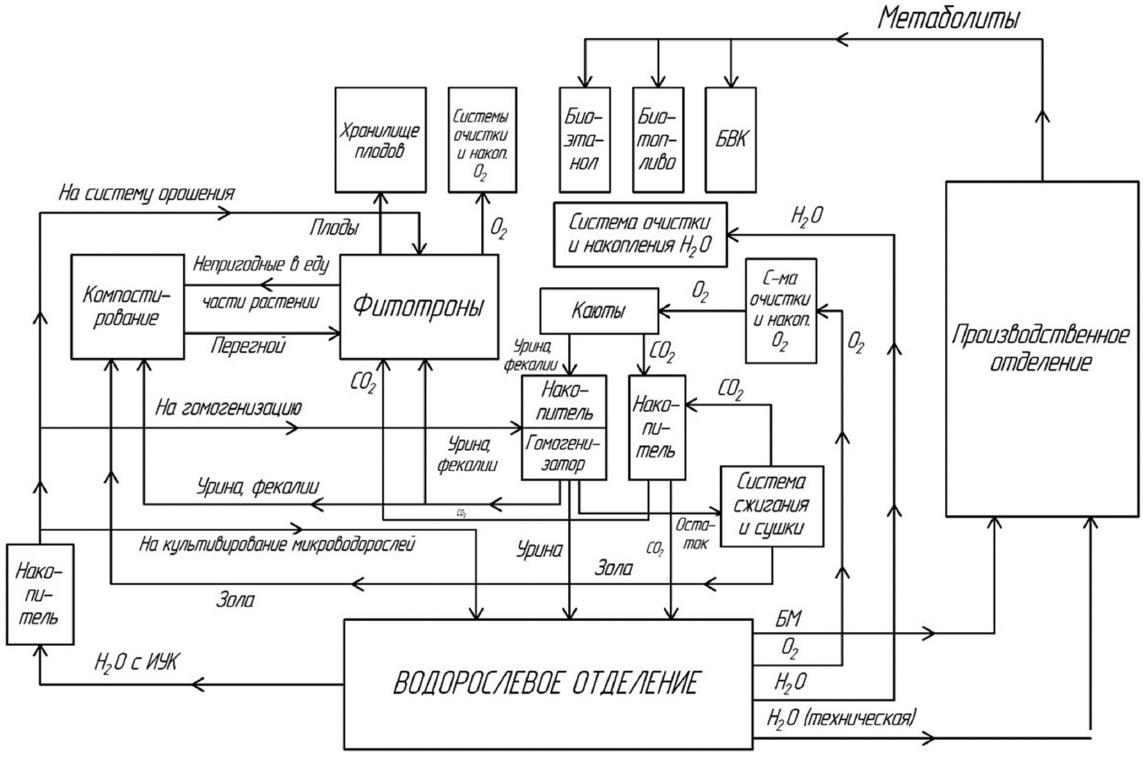


**Рис. 3.** Концептуальная схема работы комплекса системы жизнеобеспечения с использованием микроводорослей
**Fig. 3.** Conceptual scheme of the life support system complex using microalgae

*Таблица / Table*

**Сравнительная характеристика существующих и проекта предлагаемой системы жизнеобеспечения**

Comparative characteristics of existing and proposed life-support system design

| Характеристика Characteristics | БИОС-1,2,3 – СССР 1963-1977 BIOS-1,2,3–USSR 1964–1977 | БИОСФЕРА –США 1991-1994 BIOSPHERE –USA 1991–1994 | MELISSA –Испания 2009 – наст. время MELISSA –Spain 2009 - present | CEEF –Япония 1998–2007 CEEF –Japan 1998-2007 | Лунный дворец – Китай 2014 Lunar Palace – China 2014 | Предлагаемый проект Proposed Project |
|---|---|---|---|---|---|---|
| Цель | Создание замкнутой системы, позволяющей в течение большого отрезка времени имитировать земные условия при длительных космических полетах | Создание модели земной биосферы для изучения фундаментальных экологических процессов | Изучение механизмов функционирования регенеративных систем жизнеобеспечения для их применения в длительных космических миссиях | Сбор экспериментальных данных для моделирования потоков углерода в биосфере | Создание замкнутой биорегенеративной системы жизнеобеспечения | Создание системы жизнеобеспечения для применения в условиях Арктики и Крайнего Севера |
| Goal | Creation of a closed system that allows to simulate Earth conditions during long-duration spaceflight within a long period of time | Creation of a model of the Earth's biosphere to study fundamental ecological processes | Study of mechanisms of regenerative life support systems functioning for their application in long-term space missions | Collection of experimental data for modeling carbon fluxes in the biosphere | Creation of a closed bioregenerative life support system | Creation of a life support system for use in the Arctic and Far North |
| Регенерация воздуха | Выделение $O_2$, поглощение $CO_2$ микроводорослями и высшими растениями; дополнительная очистка термокаталитическими фильтрами | Выделение $O_2$, поглощение $CO_2$ высшими растениями; контроль уровня $CO_2$ при помощи газоочистительного фильтра; дополнительная очистка с использованием технологии почвенного реактора | Выделение $O_2$, поглощение $CO_2$ высшими растениями и цианобактериями | Выделение $O_2$, поглощение $CO_2$ высшими растениями; обмен $CO_2$ и $O_2$ между отдельными модулями через систему обработки газов | Выделение $O_2$, поглощение $CO_2$ высшими растениями; наличие специальной системы очистки, удаляющей следовые газы | Выделение $O_2$, поглощение $CO_2$ высшими растениями и микроводорослями; использование фильтров и других механизмов дополнительной очистки |
| Air regeneration | $O_2$ release, absorption of $CO_2$ by microalgae and higher plants; additional purification by thermocatalytic filters | $O_2$ release, absorption of $CO_2$ by higher plants; controlling $CO_2$ levels with a gas filter; additional cleaning using soil reactor technology | $O_2$ release, absorption of $CO_2$ by higher plants and cyanobacteria | $O_2$ release, absorption of $CO_2$ by higher plants; exchange of $CO_2$ and $O_2$ between individual modules through the gas treatment system | $O_2$ release,, absorption of $CO_2$ by higher plants; special cleaning system removing trace gases | $O_2$ release, absorption of $CO_2$ by higher plants and microalgae; use of filters and other mechanisms of additional purification |
| Очистка воды | Получение конденсата, его кипячение и очистка ионно-обменными фильтрами | Сбор конденсата, его использование для работы дождевой системы и орошения полей; очистка фильтрами и УФ- излучениями для получения питьевой воды | Сбор конденсата, образуемого при транспирации растений, и его дальнейшая очистка | Сбор конденсата и его использование для приготовления питательного раствора для растений и в качестве питьевой воды | Сбор конденсата из воздуха с его дальнейшей очисткой при помощи мембранных реакторов | Часть воды, очищенной в водорослевом фотобиореакторе, подвергается фильтрации и обеззараживанию для использования в качестве питьевой; другая часть применяется для полива растений в фитотроне |
| Water treatment | Collection of condensate, boiling and purifying it with ion-exchange filters | Collection of condensate, its use to run the rainwater system and to irrigate the fields; treatment with filters and UV-radiation for drinking water | Collection of condensate formed during transpiration of plants and its further cleaning | Collection of condensate and its use for preparing nutrient solution for plants and as drinking water | Collection of condensate with its further purification using membrane reactors | Part of the water purified in the algae photobioreactor is filtered and disinfected for use as drinking water; the other part is used to water plants in the phytotron |

*Окончание таблицы / The end of table*

| Характе-ристика Charac-teristics | БИОС-1,2,3 – СССР 1963 –1977 BIOS-1,2,3– USSR 1964– 1977 | БИОСФЕРА –США 1991–1994 BIOSPHERE – USA 1991–1994 | MELISSA – Испания 2009 – наст. время MELISSA —Spain 2009 - present | CEEF – Япония 1998–2007 CEEF – Japan 1998-2007 | Лунный дворец – Китай 2014 Lunar Palace – China 2014 | Предлагаемый проект Proposed Project |
|---|---|---|---|---|---|---|
| Обработ-ка отходов | Высушивание и хранение твердых человеческих отходов, использо-вание мочи для полива пшеницы, сжигание несъедоб-ных частей растений | Компостирование несъедобных частей растений и навоза животных; обработка отходов челове-ческой жизнедея-тельности при помощи анаэроб-ных баков и аэробных лагун | Разложение отходов в биореак-торе с термофиль-ным режимом работы; потреб-ление промежуточ-ных продуктов разложения фото-гетеротрофными и нитрифицирующим и бактериями | Обработка отходов при помощи реактора мокрого сжигания наряду с системой химической фиксации азота из атмосферы; пиролиз отходов человеческой жизнедеятель-ности | Разложение фекалий и несъедобных частей растений в микробном биореакторе; дистилляция мочи и удаление её сухого остатка из системы | Обработка отходов челове-ческой жизнедея-тельности путем очистки микрово-дорослями, ком-постирования, сжигания в муфельной печи. Несъедобные части растений подвергаются компостирова-нию |
| Waste treatment | Drying and storing solid human waste, using urine to irrigate wheat, burning inedible plant parts | Composting of inedible plant parts and animal manure; treatment of human waste using anaerobic tanks and aerobic lagoons | Waste decomposition in a bioreactor with a thermophilic mode of operation; consumption of intermediate decomposition products by photoheterotrophic and nitrifying bacteria | Waste treatment using a wet combustion reactor along with a system of chemical fixation of nitrogen from the atmosphere; pyrolysis of human waste | Decomposition of feces and inedible plant parts in a microbial bioreactor; distillation of urine and removal of its dry residue from the system | Treatment of human waste by cleaning with microalgae, composting, incineration in a muffle furnace. Inedible plant parts are composted |
| Культиви-рование растений | Выращивание пшеницы, чуфы, овощей в фитотронах на искусственном субстрате с применением методов гидропоники | Выращивание растений на грядках, затопленных участках рисовых плантаций, фруктовый сад; всего 86 разновидностей культур | Выращивание пшеницы, салата-латука, свеклы и других культур как на твердом субстрате, так и методом гидропоники | Выращивание методом гидропоники 23 овощных культур, включая рис и соевые бобы | Выращивание 5 видов злаков, 15 видов овощей, одного вида ягод в почвоподобных субстратах | Предлагается выращивание в почве специально отобранных злаковых и овощных культур; использование экзометаболитов микроводоро-слей в качестве стимуляторов роста |
| Cultivation of plants | Cultivation of wheat, chufa, vegetables in phytotrons on artificial substrate using hydroponic methods | Cultivation of plants on beds, flooded areas for rice plantations, orchard; a total of 86 varieties of crops | Cultivation of wheat, lettuce, beets, and other crops both on solid substrate and hydroponics | Hydroponic cultivation of 23 vegetable crops, including rice and soybeans | Cultivation of 5 types of cereals, 15 types of vegetables, one type of berries in soil-like substrates | It is proposed to grow specially selected cereals and vegetable crops in the soil; to use exometaboli-tes of microalgae as growth stimulators |
| Разведе-ние животных | Не осуществлялось | Выращивание коз, кур, свиней и рыбы. Яйца, молоко и мясо служили важным источником питания персонала | Не осуществля-лось; использова-лись лабораторные животные | Две козы | Мучные черви, использующие-ся в качестве дополнительно-го источника белка | Не планируется |
| Animal breeding | Not carried out | Raising goats, chickens, pigs and fish. Eggs, milk and meat were an important source of food for the staff | Not carried out; laboratory animals were used | Two goats | Flour worms used as an additional source of protein | Not carried out |

for three experiment participants. The remaining 2 compartments were occupied by phytotrons where wheat, chufa, and vegetables were grown [17].

The air was purified with a thermocatalytic filter that oxidized various organic impurities to carbon dioxide and water. The evaporated water was condensed and recirculated and used to prepare nutrient solutions for higher plants. Part of this water was boiled and used for household purposes and as drinking water. For this purpose, it was preliminarily passed through ion-exchange filters.

Faeces were dried and stored in a separate container, and the resulting water vapor was returned to the system; the urine entered the algae compartment and was used in the cultivation of microalgae. To close the system even more completely, a furnace designed to burn the inedible parts of the plant biomass was added [18].

*Proposed life support system project*

Based on the projects presented above, it is proposed to create a life support complex based on microalgae, whose metabolic features allow them to be used for various life support functions.

Due to their high protein content, microalgae are a promising source of valuable dietary protein [19]. The amino acid composition of the protein obtained from microalgae is balanced and meets the criteria established by the World Health Organization (WHO). It contains sufficient amounts of most essential amino acids. Microalgae cells are also rich in B and E vitamins, contain minerals and components with antioxidant, anti-inflammatory and immune-stimulating properties [20, 21].

The high percentage of lipids contained in microalgae biomass determines its potential for use as a source of 3rd generation biofuel.

Advantages of microalgae biomass compared to traditional raw materials used for biofuel production:

1. Microalgae are able to grow year-round, and as a result, their lipid productivity is much higher than that of the best oilseed varieties [22].

2. Cultivation takes place in an aqueous environment, but water consumption is less than that required to grow plants. This reduces the pressure on fresh water sources, which are in short supply in many regions [23].

3. Microalgae have a high growth rate and high lipid content. Lipids account for 20-50% of their dry biomass [24].

4. Nutrients for the cultivation of microalgae, in particular nitrogen and phosphorus, can be obtained from waste water. Thus, it is possible to combine the production of biofuel and waste treatment [25].

5. After lipid extraction from microalgae, valuable products such as protein and residual biomass can be obtained. They are used as fertilizer or livestock feed, and can also be fermented to produce ethanol or methane [26, 27].

6. The composition of microalgae biomass depends on the cultivation conditions. Thanks to this, the lipid yield can be significantly increased [28].

The fact that microalgae release phytohormones that can affect both the cells themselves and higher plants was established quite a long time ago. Semenenko's research showed the presence of indolyl-3-acetic acid in the growth medium of Chlorella sp. This acid causes stimulation of cell growth of both the algae themselves on agarized nutrient medium and wheat coleoptiles [29]. The positive effect of microalgae culture medium and extracts obtained from them on seed germination and plant growth (root length, stem height, branching, leaf and flower size) has been demonstrated in the works of many scientists [30-33]. This fact can be used in the cultivation of crops in biological life support systems.

Fig. 3 shows the conceptual scheme of the life support system complex using microalgae. Carbon dioxide that accumulates in the working and living spaces enters the algae compartment and phytotrons. There it is consumed by microalgae and higher plants.

The oxygen generated by photosynthesis is sent to the living space, the higher plants are used as a food source, and the algae biomass is used to produce protein-vitamin concentrate, bioethanol and biofuel. Human waste is purified with the help of microalgae. Some of it goes into compost or a muffle furnace. The wastewater treated by the microalgae is further filtered and disinfected. It is then used to supply the drinking water needs of personnel. The water that is not disinfected is used for technical purposes. The microalgae culture fluid containing growth stimulants is supplied to the plant watering system of the phytotron.

Comparative characteristics of the existing and the proposed life-support system project are presented in the table.

**Conclusion**

1.The use of life support systems based on biological systems will significantly increase the autonomy of infrastructure facilities located in the Arctic zone.

2. A comparative analysis showed that the most promising is the creation of life support complexes based on microalgae. Their metabolic traits make it possible to solve several important autonomy tasks simultaneously.

3. The implementation of the proposed project will provide staff with food, recycling waste, biofuel and valuable nutritional supplements.

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