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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

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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

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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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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.

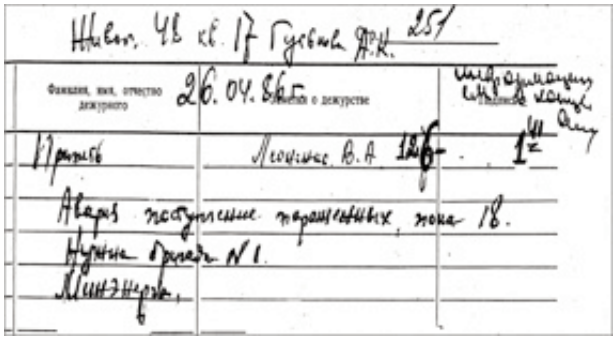

Рис.1. Запись об аварии на ЧАЭС в журнале дежурного Третьего Главного управления при Минздраве СССР: «Авария, поступление поражённых, пока 18. Нужна бригада № 1 Минэнерго»

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

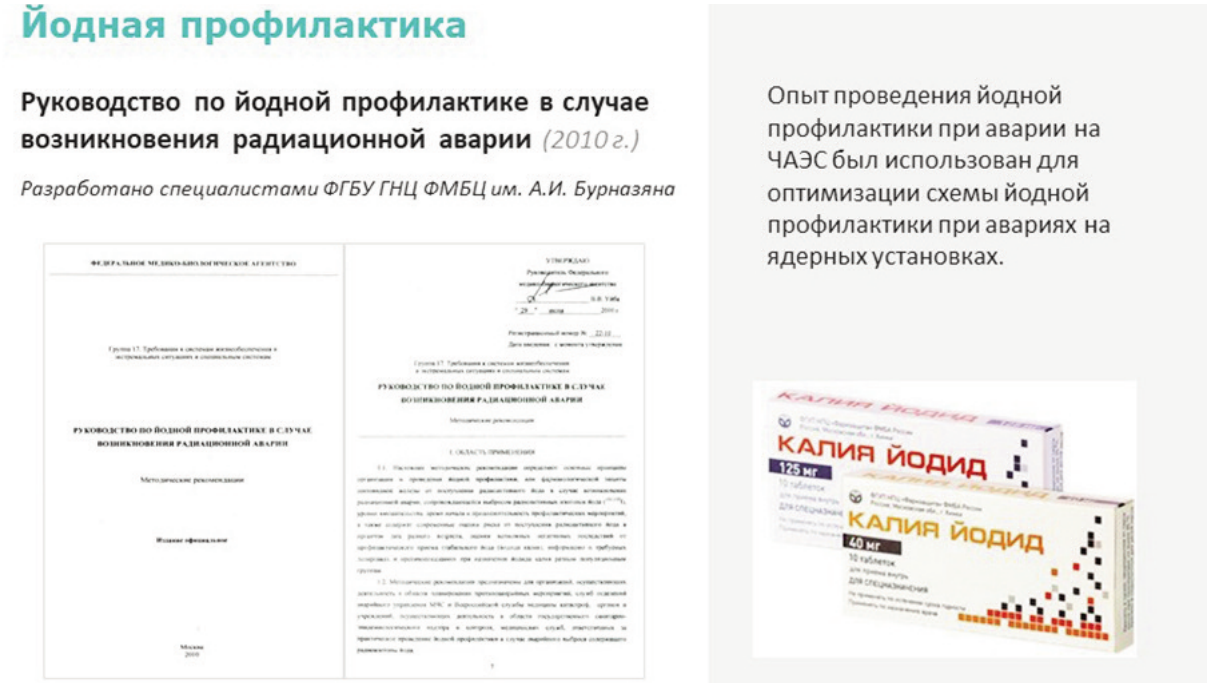

Рис. 5. Йодная профилактика / **Fig. 5.** Iodine thyroid blocking

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

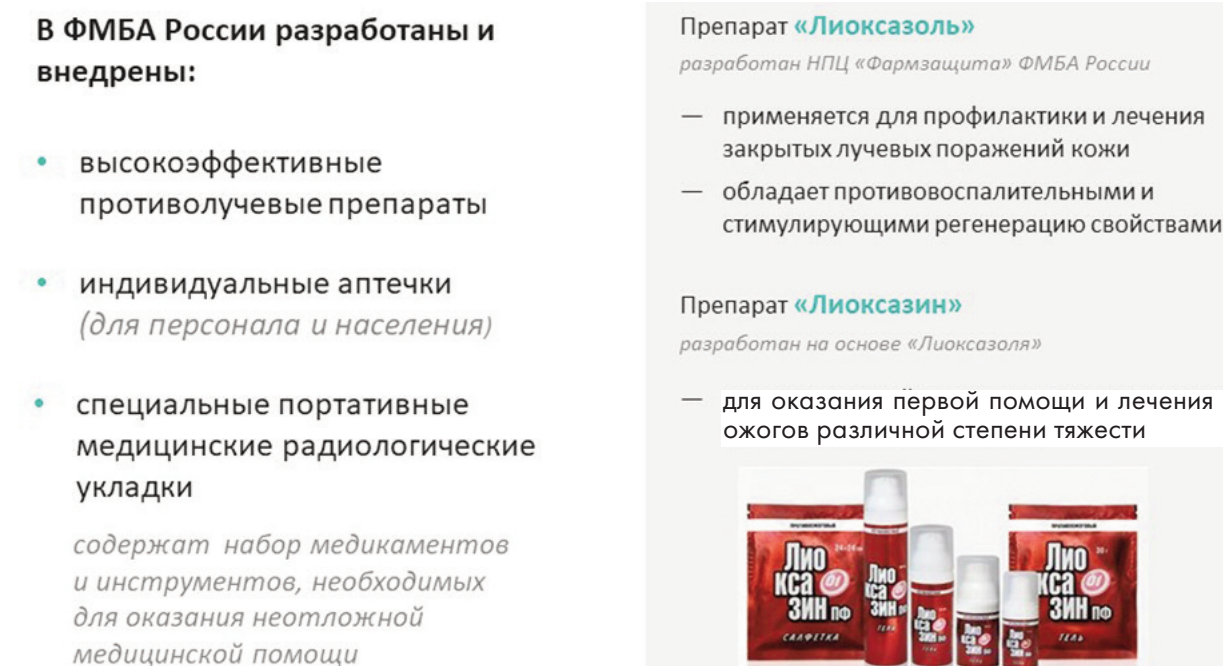

Рис. 7. Радиозащитные препараты / **Fig. 7.** Radioprotective drugs

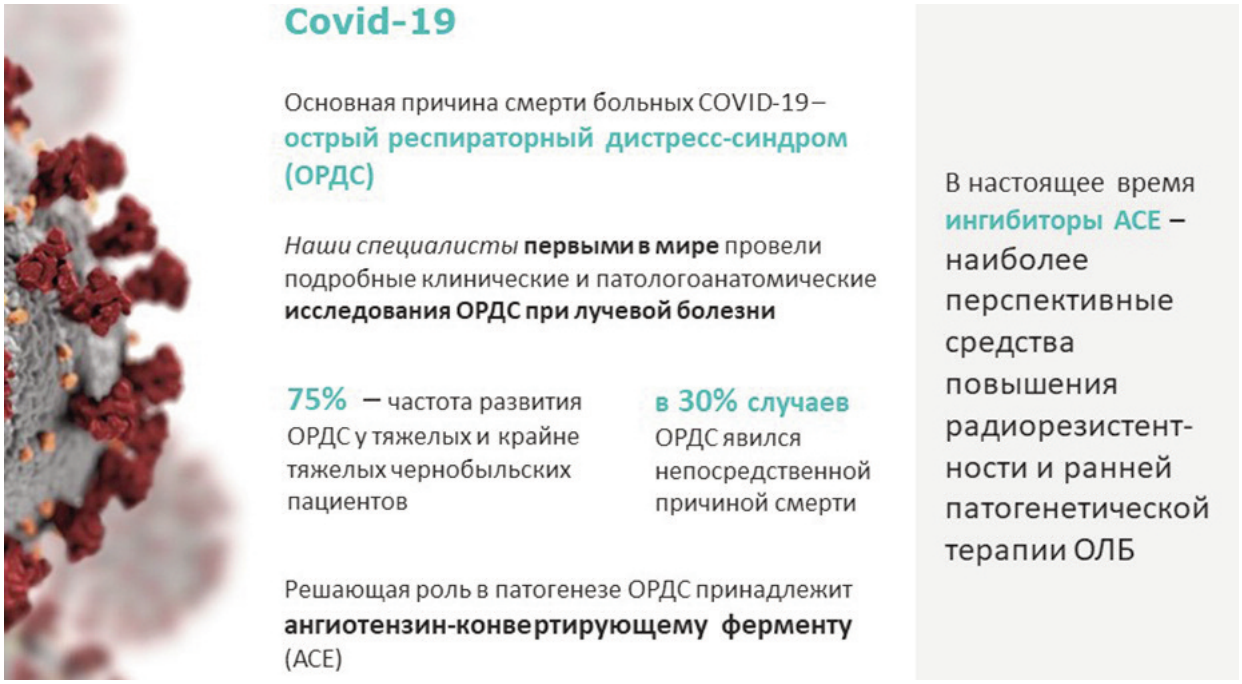

Рис. 8. Новая коронавирусная инфекция COVID-19 и острая лучевая болезнь / **Fig. 8.** COVID-19 and acute radiation syndrome

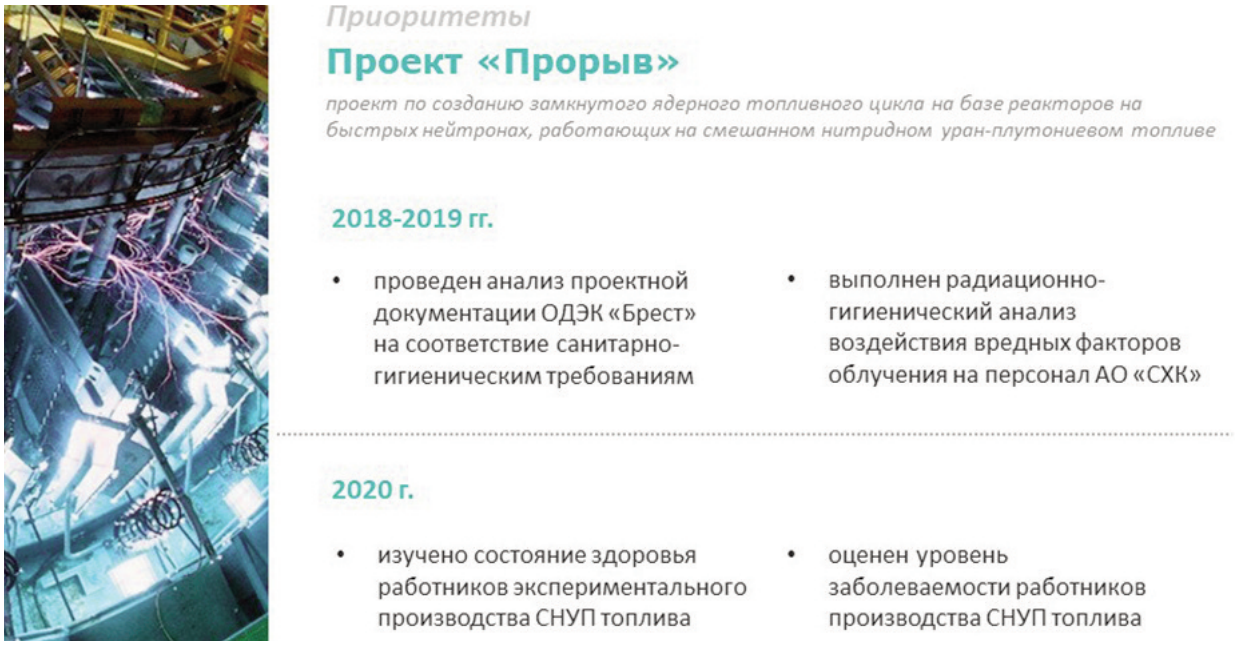

Рис. 9. Радиационно-гигиеническое сопровождение проекта «Прорыв» / **Fig. 9.** Radiation and health physics support of the "Breakthrough" project

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

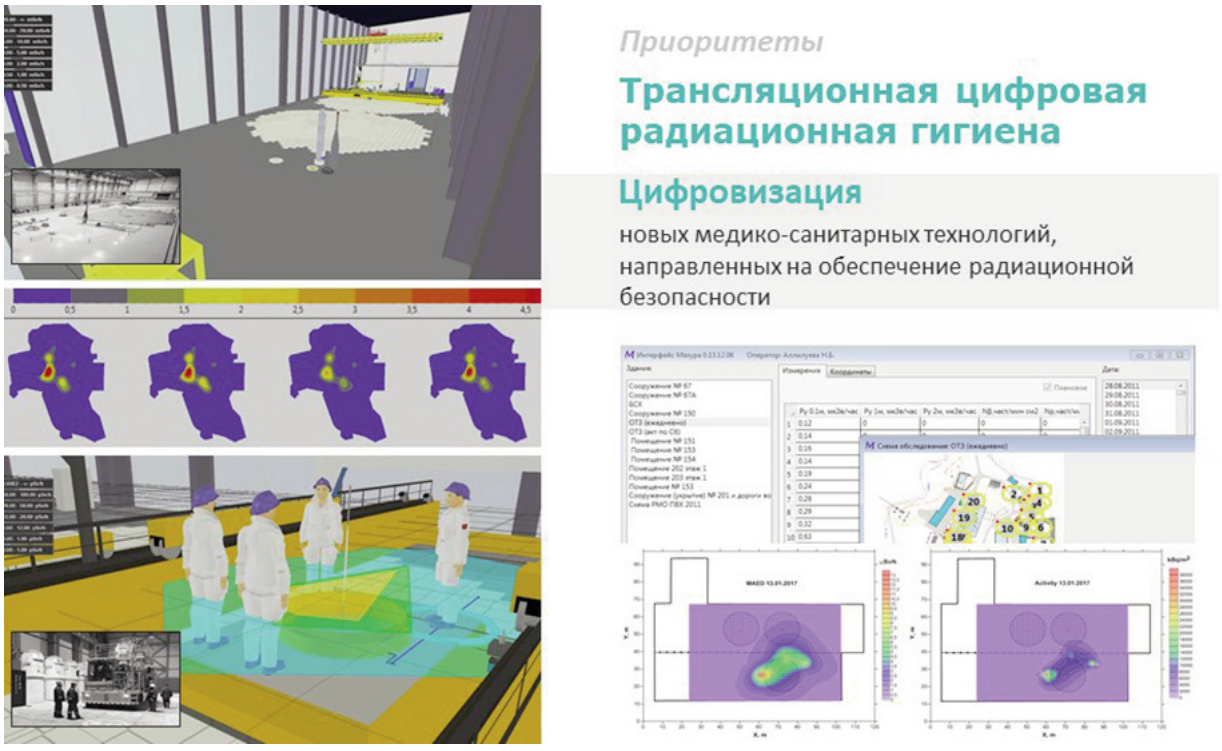

Рис. 11. Новые медико-санитарные технологии по обеспечению радиационной безопасности
Fig. 11. New medical technologies to assure radiation safety

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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