DOI: https://doi.org/10.17816/rmmar652114 EDN: COZAKQ

Current Challenges in Evaluating National Health Systems' Response to Technogenic Emergencies

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ABSTRACT
The industrial development is associated not only with economic growth but also by technogenic risks that threaten human health and the environment. Historical incidents such as the Bhopal Disaster (1984), Chernobyl Accident (1986), Fukushima Daiichi Accident (2011), Flint Water Crisis (2014), and many other technogenic accidents and disasters dramatically demonstrate the impact of existing threats to society and healthcare systems. The aim of the study was to identify key challenges and current approaches to evaluate national health systems' responses to technogenic emergencies. The study analyzed scientific publications from the NCBI, PubMed, and Elibrary databases published between 2000 and 2024. These publications underwent terminological analysis using the VOSviewer software and were peer-reviewed. Based on an analysis of the most relevant publications concerning healthcare system responses to technogenic emergencies, five key areas were identified. These areas integrate resources from healthcare facilities, management systems, and technological innovations. The study highlights the significance of an integrated approach in preparing healthcare systems for technogenic emergencies. It provides a systematic review of measures focused on improving the effectiveness of response, including simulating disaster scenarios, conducting surveys among staff and victims, raising public awareness, establishing psychological support systems, developing volunteer services, and promoting cooperation with public organizations.

Keywords: resources; healthcare system; technogenic threats; emergencies; response effectiveness.

To cite this article
Orlov SA. Current Challenges in Evaluating National Health Systems' Response to Technogenic Emergencies. *Russian Military Medical Academy Reports*. 2025;44(2):175–187. DOI: 10.17816/rmmar652114 EDN: COZAKQ

Submitted: 02.02.2025 **Accepted**: 24.03.2025 **Published**: 30.06.2025

DOI: https://doi.org/10.17816/rmmar652114 EDN: COZAKQ

Современные проблемы оценки эффективности реагирования национальных систем здравоохранения на чрезвычайные ситуации техногенного характера

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АННОТАЦИЯ

Развитие промышленных технологий сопровождается не только экономическим ростом, но и техногенными рисками, угрожающими здоровью людей и экологии. Исторические примеры, такие как аварии в Бхопале (1984), Чернобыле (1986), Фукусиме-1 (2011), кризис водоснабжения во Флинте (2014) и ряд других техногенных аварий и катастроф, являются ярким подтверждением масштаба существующих угроз для общества и систем здравоохранения. Цель: выявить ключевые проблемы и современные подходы к оценке эффективности реагирования национальных систем здравоохранения на чрезвычайные ситуации техногенного характера. Материалами для исследования стали научные публикации из баз данных NCBI, PubMed и Elibrary за 2000–2024 гг., в отношении которых были проведены терминологический анализ с использованием программы VOSviewer и экспертное рецензирование. По результатам анализа наиболее значимых публикаций для оценки реагирования системы здравоохранения на техногенные чрезвычайные ситуации установлено 5 ключевых направлений, объединяющих ресурсы медицинских организаций, системы управления и технологические разработки. В заключении исследования подчеркнута роль обеспечения комплексного подхода при подготовке системы здравоохранения к техногенным чрезвычайным ситуациям и систематизированы меры, позволяющие повысить эффективность ее реагирования, такие как моделирование сценариев катастроф, проведение опросов персонала и пострадавших, повышение уровня информированности населения, создание систем психологической поддержки, развитие волонтерства и сотрудничество с общественными организациями.

Ключевые слова: ресурсы; система здравоохранения; техногенные угрозы; чрезвычайные ситуации; эффективность реагирования.

Как цитировать

Орлов С.А. Современные проблемы оценки эффективности реагирования национальных систем здравоохранения на чрезвычайные ситуации техногенного характера // Известия Российской военно-медицинской академии. 2025. Т. 44, № 2. С. 175–187. DOI: 10.17816/rmmar652114 EDN: COZAKQ

Рукопись получена: 02.02.2025 **Рукопись одобрена**: 24.03.2025 **Опубликована**: 30.06.2025

Technological development and growth in various production sectors promote economic upturn, improve well-being, and expand access to advances in civilization. However, this progress is associated with significant issues resulting from violations related to technological processes, the leakage of hazardous or toxic raw materials, and deliberate destructive acts in locations at high technological risk, especially in an unstable global geopolitical context.

Technological accidents and disasters[1] present significant hazards to the environment, public health, and human life. Their incidence has been increasing each year. The first major disaster occurred in Bhopal, India, in 1984. A 40-ton leak exposed approximately 500,000 people to methyl isocyanate, which is a toxic lachrymatory gas. Approximately 4000 people immediately died, and thousands of premature deaths, diseases, and environmental problems followed, including an increased risk of birth defects and pediatric cancer [1, 2]. The 1986 accident at the Chernobyl nuclear power plant in the USSR is the most well-known technological disaster that caused widespread radioactive contamination, acute radiation syndrome, numerous hospitalizations, and subsequent cancer-related deaths [3]. In 2006, the World Health Organization (WHO) reported that approximately 9000 people who were exposed to high doses of radiation died of radiation-related cancers. Other notable technological emergencies include the 2014 Flint Water Crisis in the United States, which resulted in lead leaching into the water supply and negatively impacted children's mental development; and the 1957 Windscale fire, which occurred at the Windscale (Sellafield) nuclear power plant (England, 1957) and resulted in 470 male workers involved in the firefighting efforts and subsequent clean-up becoming ill and dying of cancer. The 1957 Mayak accident in Kyshtym, USSR, caused 26 cases of solid cancer diagnosed in exposed individuals over a 50-year observation period. The 2011 Fukushima Daiichi accident in Japan is predicted to result in approximately 5,000 cancer-related deaths in the future. The 2015 chemical warehouse explosion in Tianjin, China, resulted in 158 deaths and 698 hospitalizations [4–8].

Since its launch in 1988, the Emergency Events Database,[2] developed by the Center for Research on the Epidemiology of Disasters and WHO, has recorded over 26,000 significant disasters[3] between January 2000 and August 2024. Among these disasters, >900 are technological disasters belonging to the Technological Disaster group and Industrial Accident subgroup. These emergencies resulted in approximately 26,000 deaths and 38,000 injuries.[4]

Therefore, it is crucial to ensure an effective response from the healthcare system during the acute and long-term phases of a disaster. This response should consider the long-term environmental consequences of substances released into the air, soil, water, and food as a result of technological emergencies and address their negative impact on public health and well-being.

The study *aimed* to evaluate scientific publications and consider key issues and current approaches to assessing the effectiveness of the response of national healthcare systems to technological emergencies.

Scientific studies were reviewed to evaluate the current issues related to technological threats that affect national healthcare systems. The first stage of the study involved compiling a database of publications from the *National Library of Medicine*[5] and *PubMed* from January 1, 2000, to December 31, 2024. The database was created using terms consistent with the *Medical Subject Headings* system. The query syntax included the following terms and their morphological variants: man-made disasters OR technogenic accident OR industrial disaster OR technogenic disaster OR technological disaster AND healthcare system.

During this stage, the bibliometric and visual analysis tool VOSviewer 1.6.20 was used to illustrate the semantic connections between the main terms and concepts characterizing the impact of technological challenges on public health, the healthcare system, and the planning and activities of medical organizations.

In the second stage of the study, the sample of international publications was supplemented with Russian publications from *eLIBRARY.RU* using the phrase *техногенные угрозы* (technological threats/hazards), with morphological variations, from January 1, 2000 to December 31, 2024.

In the third stage, studies that were not scientifically relevant to the research topic were excluded through expert review. Thus, a final sample of foreign and Russian publications was formed.

In the fourth stage, content analysis was performed using the most informative publications that characterized the current issues of evaluating the effectiveness of national healthcare systems in responding to technological emergencies.

The study sample included 544 eligible articles. The scientific publications were combined into five ontological clusters based on the strength and frequency of keywords (phrases) that characterized each cluster (Fig. 1).

[1] The terms and definitions established by the National Standard of the Russian Federation GOST R 22.0.05-2020 "Emergency Safety. Technological emergencies. Terms and Definitions" are used hereinafter.

[2] https://public.emdat.be/

[3] These include disasters that meet at least one of the following criteria: at least 10 deaths; at least 100 injuries; a declaration of a state of emergency; and an International Assistance request.

[4] Hereinafter, the term is used in the meaning defined by the National Standard of the Russian Federation, GOST R 22.0.02-2016 "Emergency Safety. Terms and Definitions."

[5] https://www.ncbi.nlm.nih.gov

DOI: https://doi.org/10.17816/rmmar652114

The most significant keywords for the first cluster, which focused on the accessibility of medical care and cross-departmental cooperation, were *работа по оказанию помощи* (*relief work*), *потребность в медицинских услугах и спрос на них* (*health services needs and demand*), *доступность медицинских услуг* (*health services accessibility*), *and международное сотрудничество* (*international cooperation*).

The most significant keywords (phrases) for the second cluster, which characterized the resource capabilities of medical organizations, included *наращивание потенциала* (*capacity building*), and *стратегический запас для оказания медицинской помощи* (*strategic stockpile for health care delivery*).

The most significant keywords (phrases) for the third cluster, which reflected accumulated experience in responding to technological emergencies, were *знания, отношение и практика в области здравоохранения* (*health knowledge, attitudes, practice*), *планирование действий в случае стихийных бедствий* (*disaster planning*), *отношение медицинского персонала* (*attitude of health personnel*), and *оценка потребностей* (*needs assessment*).

The most significant keywords (phrases) for the fourth cluster, which combined parameters characterizing the possible consequences of man-made factors on the population and healthcare system, consisted of *воздействие окружающей среды* (*environmental exposure*), *спасательные работы* (*rescue work*), *стресс, психологические факторы риска* (*risk factors stress, psychological*), and *психические расстройства* (*mental disorders*).

The fifth cluster aggregated terms that reflected damage caused by technological emergencies, as expressed by parameters such as *раны и увечья* (*wounds and injuries*), *смертность* (*mortality*), and *разрушения, в том числе в отношении мест проживания населения* (*housing*).

Analysis of scientific publications identified the following key factors that determine the preparedness of national healthcare systems to effectively respond to technological emergencies: groups of resources of medical organizations directly involved in providing care to injured individuals (medical personnel, equipment, medicinal products, and medical devices); systems that organize, support, and monitor emergency treatment processes, interdepartmental interaction, and work coordination; and systems that inform the population in affected zones (warning systems, case recording, monitoring the spread of man-made factors, and recording medical consequences).

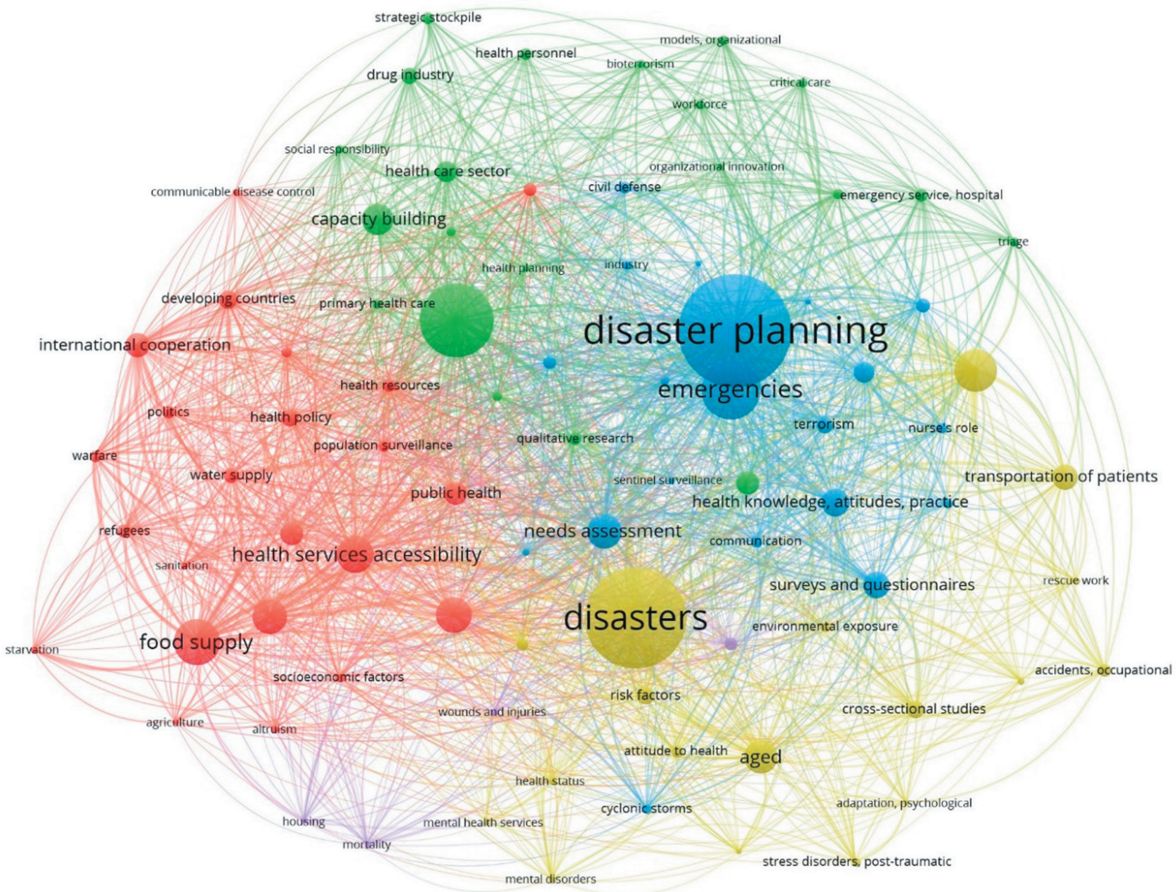

Fig. 1. A semantic network of the linguistic connections between key terms and concepts that characterize the impact of technological threats on healthcare systems.

DOI: https://doi.org/10.17816/rmmar652114

Medical personnel can effectively respond to technological threats through the interaction of various components that ensure prompt, high-quality medical care.

Effective functioning in various emergency situations, including technological ones, requires stable *laws and regulations* that describe the actions of medical personnel and distribution of responsibilities among different levels of the healthcare system [9, 10].

A unified *management and coordination system* is required for medical personnel to facilitate prompt decision-making; this can be achieved by establishing a single Personnel Management Center. This center should operate according to clearly defined protocols for responding to technological accidents and disasters and facilitate seamless interaction with other services, such as the Ministry of Emergency Situations of Russia, Ministry of Internal Affairs of Russia, and Federal Service for the Oversight of Consumer Protection and Welfare (Rospotrebnadzor) and public utilities [11, 12].

Medical personnel should *undergo regular training to prepare* for any technological hazard scenario. This simulation training should resemble real-life situations and include providing emergency care in cases of burns, injuries, and exposure to toxic substances and radiation [13–15].

It is crucial to provide medical personnel with *information and analytical support* and timely and comprehensive access to monitoring and early warning systems for technological threats and to databases containing critical information about injured individuals, chemical substances, and other technological factors [16].

Medical personnel should be equipped with modern diagnostic and treatment equipment to provide high-quality and prompt medical care to injured individuals and ambulances and other medical transportation to swiftly evacuate injured individuals from the affected zone to specialized medical organizations. Moreover, they should have an adequate supply of medicinal products and dressings and use personal protective equipment (PPE), such as protective masks, suits, and filters, to minimize the harmful effects of technological factors on health of physicians and nurses. If needed, the healthcare system should be able to mobilize medical personnel and resources from other regions and should involve other departments and services [17].

In addition to understanding technological factors, medical personnel should possess the required skills to provide psychological support in extreme conditions to effectively interact with injured individuals in emergency situations [18].

The integration of technology with the organization and operations of medical equipment is another critical factor in the preparedness of a national healthcare system for technological emergencies. This includes mobile health units and field hospitals; ambulances with intensive care and monitoring equipment; diagnostic equipment, such as mobile X-ray and ultrasound machines and computed tomography scanners; vital function monitors for assessing injured individuals; and intensive care equipment, such as artificial lung ventilation machines, defibrillators, infusion pumps, and blood purification and detoxification machines. In addition, the implementation of *innovative technologies* significantly simplifies interactions between the healthcare system and patients. These technologies include robotic systems and unmanned aerial vehicles for delivering medical supplies and biological samples and telemedicine technologies for remote consultations with medical experts and digital platforms for supporting emergency data management systems. These technologies ensure the quality of medical care [19–22].

To overcome the consequences of technological factors, issues related to *logistics* and *transport* services for medical equipment in affected zones should be promptly resolved. The key components of this process include the quick delivery of medical equipment to the affected zone, specialized transportation such as air ambulances and trucks equipped with medical supplies, and flexible equipment capable of operating in challenging conditions (folding and deploying and performing multiple tasks) [23].

A *mobilization reserve* should be established at every healthcare system level. The system should be able to swiftly re-equip with medical equipment for use in technological accidents and disasters. Regular *maintenance* and *repairs*, including serviceability checks and personnel training to work with and maintain the equipment, should be considered [24].

At the *regulatory* level, operating the healthcare system during technological accidents and disasters requires compliance with medical equipment standards and protocols for use in emergency zones and with operational regulations.

The ability of a national healthcare system to effectively respond to technological challenges largely depends on the availability of medicinal products and medical devices. Key components include *establishing* and *maintaining* strategic reserves, including storing sufficient medicinal products (e.g., antidotes, analgesics, resuscitation agents, and detoxification agents) and medical devices (e.g., dressings, splints, disposable masks, and suits) in close proximity to areas at risk of technological accidents and disasters; effective *logistics and transportation*, including rapidly delivering these supplies to affected zones and using automated control systems for real-time accounting, tracking, and spread; and *swiftly adapting* and flexibly adjusting production capacities to rapidly increase the production of needed medicinal products (e. g., antidotes and toxin neutralizers) [25–28].

Innovative technologies are crucial for healthcare systems to respond to technological threats. For medicinal products and medical devices, this could include artificial intelligence technologies and data analysis based on risk assessment or the spread of technological threats. It could also include technologies for manufacturing new medicinal products, such as fast-acting antidotes, syringe tubes, and transdermal patches that rapidly deliver active substances [29, 30].

During a global technological challenge, the legal *regulation* and *certification* of individual medicinal products[6] and medical devices[7] (e.g., experimental developments) should be optimized to ensure free access to these products and create unified protocols for the rapid selection, use, and replacement of medicinal products and medical devices.

Medical personnel should undergo proper *training* and adhere to distribution protocols aimed at minimizing losses and promoting the rational use of medicinal products and medical devices to improve their awareness of the proper use of these products.[8]

Furthermore, to ensure *the stability of medicinal and other products (e.g., immunobiological agents)*, medical organizations in the healthcare system should comply with storage requirements,[9] such as using warehouses with controlled temperature conditions and technologies that increase shelf life, such as lyophilization and hermetically sealed packaging [31].

During a technological challenge, the stock of medicinal products (e.g., antidotes and specific agents) and universal medical devices in medical organizations should be *oriented toward current and future needs,* considering prevalence and degree of damage to the local community [32].

Warning and incident reporting systems adapted to the needs of emergency medical services and used by relevant *command and coordination centers*, such as emergency medical care centers, coordination structures, mobile medical centers, and field hospitals, enable the healthcare system to effectively respond to technological emergencies and incidents [33].

These systems should include a medical component to establish a rapid response, minimize damage, and prevent casualties. The systems can be structured as follows:

Medical alert systems such as mobile applications and SMS alerts that inform the population about emergencies, evacuations, precautions, available medical services, and assembly points; subsystems that automatically alert medical personnel about incidents, expected patient flows, and the need to prepare for emergency situations; and subsystems that identify and classify emergency messages using codes to rapidly identify incident types, such as chemical poisoning, radiation threats, and mass poisoning

Information systems and databases such as those for recording and reporting casualties, centralized patient databases, and systems for monitoring medical supplies (medicinal products, equipment, and blood and its components).

Systems for monitoring and evaluating incidents, including information panels to monitor data on incidents, casualties, and levels of damage; systems to predict the spread of diseases arising from technological incidents and evaluate and process data on the causes and consequences of incidents

Communication and support systems including remote counseling and psychological assistance for injured individuals and medical personnel and informing the population [34–37].

The last element of an effective healthcare system's response to technological threats involves monitoring systems to track the spread of these threats and document their medical consequences. The systems can be classified as follows:

Technological systems such as sensors and detectors installed in high-risk areas to detect chemical, biological, radiation, and physical factors (gas analyzers, radiometers, thermal imagers, etc.) and mobile spread monitoring systems

Information and analytical systems such as early warning systems based on predictive models using data on the spread of technological factors (e.g., explosions, leaks, and pollution) and geographic information systems (e.g., interactive maps for displaying the spread of threats and assessing affected zones)

Aggregation systems such as cloud and online services for interdepartmental interaction and aggregators of data from industrial enterprises, meteorological stations, social and hygienic monitoring, etc.

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[6] Resolution no. 441 of the Government of the Russian Federation *On Special Considerations Relating to Circulation of Medicinal Products Intended for Use in Possible or Actual Emergencies, Delivery of Emergency Health Care, Prevention of Emergencies, Prevention and Treatment of Diseases That Pose a Threat to the Public as well as Diseases and Injuries Caused by Exposure to Adverse Chemical, Biological, Radiation Factors* dated of April 3, 2020. Available at: https://www.consultant.ru/document/cons_doc_LAW_349474/

[7] Resolution no. 430 of the Government of the Russian Federation *On Special Considerations Relating to Circulation of Medical Devices, including State Registration of a Batch (Lot) of a Medical Device* dated April 3, 2020. Available at: https://www.consultant.ru/document/cons_doc_LAW_349469/

[8] Timoshevskiy AA, Konev VV, Khalyutin DA. "Preparation and Operations of Medical and Pharmaceutical Organizations in Emergency Situations: A Textbook." Moscow: Research Institute for Healthcare and Medical Management of Moscow Healthcare Department (NIIOZMM DZM), 2024. 56 p. Available at: https://niioz.ru/moskovskaya-meditsina/izdaniya-nii/metodicheskie-posobiya/

[9] Order no. 760n of the Ministry of Health and Social Development of the Russian Federation *On Approval of the Rules for the Storage of Medicinal Products* dated August 23, 2010. Available at: https://www.consultant.ru/document/cons_doc_LAW_105562/

DOI: https://doi.org/10.17816/rmmar652114

Software tools for modeling and calculating affected zones and the spread trajectories of chemical and radioactive substances and for automatically notifying the population and response services

Medical monitoring systems such as electronic medical records of patients and biometric devices that monitor the health status of injured individuals [38–46].

Assessing the effectiveness of responses to technological emergencies is challenging because of some problems associated with the complex and multifactorial nature of the task.

First, countries and organizations assess the effectiveness of responses differently. Each country uses its own methods and standards based on its unique circumstances and available resources. Russia has extensive experience in studying the effectiveness of medical support and the organization and management of medical care for people injured in technological emergencies. This has been primarily achieved through the efforts and resources of the All-Russian Disaster Medicine Service (ARDMS),[10] which is a functional subsystem of the Unified State System for the Prevention and Elimination of Emergency Situations [47–50].[11] The Russian response system is constantly improving based on lessons learned from past disasters. The All-Russian Center for Disaster Medicine "Zashchita" evaluated the zoning and planning strategies used for protective measures around nuclear power plants. These strategies were proven effective following the 2011 Fukushima Daiichi accident in Japan [50]. In 1999, the Ministry of Emergency Situations of the Russian Federation established the Center for Emergency Psychological Aid, which has increased the effectiveness of assistance provided to injured individuals and their families in emergency situations [51]. With the development of regulatory frameworks and training programs, ARDMS now has mobile units and hospitals that can be rapidly deployed to disaster zones. Russian mobile units are among the world's leaders. A multidisciplinary field hospital and the Centrospas unit of the Ministry of Emergency Situations of the Russian Federation were among the first to undergo WHO certification and fully complied with international Emergency Medical Teams standards. However, some aspects of resource provision still require greater development of air ambulance services and their usage [52].

In the United States, the Federal Emergency Management Agency (FEMA), which is part of the Department of Homeland Security, coordinates disaster response efforts [53]. FEMA is responsible for mobilizing federal disaster rescue and medical resources at a state's request. Moreover, the United States has a National Disaster Medical System (NDMS), which includes Disaster Medical Assistance Teams (DMATs), among other rapid deployment units. DMATs are teams comprising physicians, paramedics, and other specialists. They are provided with self-contained kits for field deployment. After the terrorist attacks of September 11, 2001, and subsequent bioterrorism incidents such as the anthrax attacks, the United States started training more medical personnel for emergency situations. Disaster response courses have been included in medical school and college curricula, especially in nursing programs. Currently, required early response skills include the ability to provide medical assistance and psychological support and to communicate with injured individuals under stressful conditions [54]. The American system has several strengths, including extensive material and personnel resources; the ability to swiftly deploy field hospitals; a well-established air ambulance and evacuation system; and a robust volunteer culture. However, the healthcare system of the United States is fragmented across states, which sometimes causes coordination problems. Hurricane Katrina in 2005 revealed shortcomings in the evacuation planning for victims, showing that medical and rescue services at different levels were unable to immediately coordinate their efforts. These lessons led to corresponding reforms. Hospital preparedness plans were revised, a unified communication system was established for all services, and more attention was focused on the evacuation of vulnerable groups. The United States generally demonstrates high efficiency in technological emergencies; however, success largely depends on advance preparation and clear command in the first hours after a disaster.

In China, an emergency response system has significantly evolved since the early 2000s, particularly after the severe acute respiratory syndrome outbreak in 2003 and the Sichuan earthquake in 2008. In 2005, the National Commission for Disaster Reduction was established to coordinate efforts, bringing together 34 ministries and agencies, including military structures [55]. The Chinese approach is characterized by the close integration of People's Liberation Army (PLA) resources into the disaster medicine system. Military hospitals have highly qualified personnel, transport, and mobile hospitals that can be rapidly deployed to emergency zones. Twenty-two national medical emergency response teams have been established and deployed across different regions of the People's Republic of China since 2010 [55]. Many of these centers are based in military hospitals and are equipped

[10] Order no. 1202n of the Ministry of Health of the Russian Federation *On Approval of the Procedure for Organizing and Providing Medical Care in Emergency Situations, including Medical Evacuation, by the All-Russian Disaster Medicine Service* dated November 6, 2020. Available at: https://www.consultant.ru/document/cons_doc_LAW_367840/

[11] Resolution No. 794 of the Government of the Russian Federation *On the Unified State System for the Prevention and Elimination of Emergency Situations* dated December 30, 2003. Available at: https://www.consultant.ru/document/cons_doc_LAW_45914/

DOI: https://doi.org/10.17816/rmmar652114

with portable equipment and autonomous life-support resources, allowing them to operate independently of local stock levels and support resources. These teams are equipped to set up field hospitals, triage the wounded, and evacuate critically ill patients to major medical centers. In 2015, after a series of explosions at the Port of Tianjin, hospitals in Tianjin and neighboring cities mobilized by setting up additional departments and calling in hundreds of surgeons and nurses [56]. The Tianjin incident emphasized the benefits of rapidly allocating resources, such as the deployment of PLA medical personnel. However, it also revealed the challenges posed by a lack of coordination and information sharing between hospitals. China has made significant progress in emergency preparedness by establishing a unified warning system, conducting periodic simulated exercises, and developing remote monitoring systems. However, scientific reviews reported several challenges that hinder the effectiveness of the response. These include insufficient protection of healthcare infrastructure, with many hospitals being vulnerable to destruction (e.g., up to 67.5% of medical buildings collapsed in affected areas during the 2008 earthquake); lack of detailed action plans for rare disasters in some hospitals; weak coordination between hospitals during a mass influx of injured individuals; and limited portable equipment and trained personnel for field triage and intensive care [55]. The emergency medical care system was fragmented between urban and rural areas, and emergency legislation and funding allocation were not fully regulated.

Japan also had extensive experience in responding to natural and technological disasters, which has significantly affected the organization of its disaster medicine system. The 1995 Great Hanshin-Awaji Earthquake was a turning point, resulting in 6434 deaths and over 43,000 injured individuals [57]. An analysis showed that many of the victims could have been saved; however, at that time, the country had no national system for medical response to disasters, and medical care was uncoordinated [57]. In response, Japan established its NDMS. The system included disaster base hospitals in each region equipped to receive large numbers of injured individuals and a national emergency medical information system and DMATs, which are mobile teams dispatched to emergency zones. It also involved an air ambulance system for evacuations that used aircraft and helicopters of Self-Defense Forces. The effectiveness of this system was tested during the *Tōhoku* earthquake and tsunami (the Great East Japan earthquake) and the subsequent accident at the Fukushima Daiichi Nuclear Power Plant in March 2011. Within 24 h of the disaster, approximately 78 DMATs, consisting of approximately 393 specialists, were mobilized and flown to the affected region by Air Force transport aircraft. Field medical stations were set up near the disaster area at Self-Defense Force bases and airfields. The wounded were triaged and evacuated through these stations [57]. In the first days of the operation, air ambulances evacuated dozens of critically ill patients from coastal areas where local hospitals had been destroyed or lost power. The Japanese Medical Association Teams also participated in the relief efforts by providing assistance at evacuation centers and conducting medical examinations of the deceased [58]. The Japanese response is characterized by a high level of organization and discipline. A clear distribution of responsibilities among services, including fire and rescue units, the Self-Defense Forces, medical teams, and the prefectural administration, prevents chaos, even in extreme conditions. Japan conducts a detailed review after every major emergency and enhances plans based on the results. The lessons learned from the Fukushima accident have led to revisions in hospital evacuation protocols for radiation emergencies and the development of backup power systems for healthcare facilities. The Japanese system demonstrates three main strengths: nationwide coverage (with several DMATs and base clinics in each prefecture), the capacity to rapidly deploy resources via a centralized command center, and a culture of public engagement (wherein the population is educated in fundamental first aid and emergency response procedures).

In the European Union (EU), each country has its own emergency medical system; however, they generally have similar features, such as a well-developed ambulance service, close cooperation between emergency services, and national response reserves. Germany has adopted the Doctor at the Accident Scene concept, wherein an emergency physician responds to injured individuals in the pre-hospital setting. The German emergency medical services (*Rettungsdienst*) are well-equipped. However, until recently, there were unresolved organizational issues. There was no single emergency number (historically, there were different numbers), and hospitals did not have integrated, multidisciplinary emergency departments [59]. Germany has a unified state system for major emergency response and recovery. Other structures are also involved if needed, including the police, firefighters, the *Technische Hilfswerk* technical assistance service, and charitable organizations such as the Red Cross and *Johanniter-Unfall-Hilfe*. France has a similar emergency medical system called the *Service d'Aide Médicale Urgente*, which ensures that teams of physicians and paramedics quickly reach accident scenes. The EU prioritizes providing victims with the fastest possible medical assistance and transporting them to specialized hospitals. The EU has created a mechanism to coordinate emergency response efforts that exceed the capabilities of a country. The Union Civil Protection Mechanism brings together 34 European countries, enabling any affected country to request assistance from its neighbors.[12] This mechanism reserves assistance modules, such as fire, rescue, and medical teams, which are ready for rapid dispatch to disaster areas. Following the severe shortage of trained medical teams during the 2014 Ebola epidemic, the EU established the European Medical Corps, which is a network of certified medical teams from various countries that can be swiftly deployed to deliver medical care within or outside the EU.[13] The EU's Emergency Response Coordination Center organizes such missions. The teams are prequalified according to high standards, including those of WHO, and are trained to work together. The European Medical Corps includes surgical field hospitals and ambulance teams from Germany, France, Spain, and other countries. The advantage of the EU approach is the ability to rapidly escalate force levels as required, ensuring a mutual assistance effect. In the event of an explosion at a chemical plant in France or a technological accident in Hungary, additional ambulances, medical supplies, and medical teams from other countries could be sent to the affected area. The EU regularly holds joint exercises and develops scenarios for technological accidents or disasters to facilitate the exchange of best practices.[14] However, establishing unified protocols and communication standards remains challenging. Members of a multinational team may employ different standards. To solve this problem, the European Medical Corps introduced a certification system with uniform requirements.

Despite significant advances in disaster medicine services in various countries, there is currently no standardized methodology for conducting objective, comparative studies on the effectiveness of responses to technological emergencies. This gap becomes apparent during international disasters that require cooperation between various countries. The problem is further complicated by the fact that some methodologies focus on specific aspects, such as response or healthcare delivery time. A more comprehensive approach that considers social and economic impacts is less common. Using a consistent methodology allows for the development and implementation of standardized recommendations at the national and international levels. One way to evaluate the effectiveness of national healthcare systems' responses to technological emergencies, including their medical, social, and economic components, is to develop an integral index. This index is calculated by adding the expert scores for a set of parameters. The medical component of this index may include the time it takes to administer first aid, percentage of injured individuals who receive medical care within the "golden hour" (the critical 60 min after an accident), and level of equipment and staffing of the emergency medical team. This may also include parameters that characterize the quality of medical care, such as mortality and postsurgical complication rates, and adherence to clinical guidelines (treatment protocols). The social component of the index may cover government-provided social support, emergency awareness, the availability of social and psychological assistance, and the number of complaints and appeals and how appropriate services and departments address them. Furthermore, the economic component of the index should cover the estimated costs of mobilizing emergency services, purchasing medical supplies and equipment, arranging transportation, renovating and equipping hospitals, rebuilding infrastructures, compensating the victims' families, and funding temporary housing programs. It should also encompass indirect losses resulting from a decrease in business activity, including loss of gross regional or domestic product, business downtime, loss of work capacity among certain population groups (e.g., increased days of work incapacity or temporary or permanent loss of personnel), and increased personal expenses (e.g., temporary accommodation costs). In this context, a promising area for future research is to formalize criteria and develop a methodology that considers a set of mathematical expressions to establish a range of index values, which would qualify response of the healthcare system to technological emergencies.

Second, technological accidents and disasters may provide inaccurate assessments of the current situation because of limited data. Information is often received late, contains errors, or is incomplete owing to data confidentiality. Communications may be disrupted in disaster areas, resulting in a lack of real-time data regarding the number of people affected by the emergency, their conditions, and the availability of resources. Moreover, creating a statistical database for developing decision and response models is challenging. In addition, historical data has some limitations because each emergency is unique, making it difficult to use them for forecasting and assessment. This requires the development of new methods that enable real-time data collection and prompt adaptation of response measures.

Third, technological emergencies are often multidisciplinary. Accidents and disasters at chemical plants can have serious consequences, including physical injury, toxicological effects, and mental health issues, and a long-term environmental effect. Another challenge is to consider all these aspects when evaluating response effectiveness. Various factors should also be considered, including weather conditions, population density in the

[12] https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/eu-civil-protection-mechanism_en

[13] https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/european-medical-corps_en#:~:text=Why%20is%20this%20important%3F

[14] https://eufundingoverview.be/funding/eu-civil-protection-mechanism-ucpm#:~:text=EU%20Civil%20Protection%20Mechanism%20,the%20exchange%20of%20best%20practices

emergency zone, and the preparedness of local services. This complicates the analysis process and makes the results less predictable.

Fourth, significant differences in funding, staffing, and technical equipment levels indicate that healthcare systems have varying abilities to cope with crises. Even in developed countries, the availability of resources can vary in every region. In rural areas, the lack of medical personnel and specialized equipment often hinders the area's ability to respond to emergencies. This problem requires developing reserve resources and integrating private and public structures into a unified response system.

Fifth is a lack of a long-term monitoring system. Once emergency response activities are completed, attention to post-crisis research significantly decreases. This prevents healthcare systems from learning valuable lessons from their experience and preparing for similar events in the future. Using monitoring systems to record short- and long-term emergency consequences can significantly improve response quality and minimize negative effects.

Sixth is a lack of clear criteria and key performance indicators (KPIs). KPIs are beneficial for assessing the healthcare system based on parameters such as response time, availability of medical services, and mortality and morbidity rates. These indicators may include the average time it takes to transport injured individuals to healthcare facilities; percentage of survivors with severe injuries or poisoning; and availability of resources, such as medical supplies, equipment, and personnel. Moreover, it is crucial to understand that each emergency is unique. Chemical and radiation disasters require different approaches to assessing the effectiveness of responses.

CONCLUSION

The preparedness of national healthcare systems and medical organizations for technological emergencies is a critical task, especially in the Russian Federation. The following areas should be prioritized to improve the preparedness of the healthcare system: modeling and simulation, surveys and questionnaires, comparative analysis, public awareness, psychological support, social partnerships and volunteering, and trust in the healthcare system.

The actions of the healthcare system can be evaluated and its weaknesses may be determined using modern artificial intelligence technologies to create scenarios of technological accidents and disasters. Computer simulations can model the spread of toxic substances and evacuation flows. In addition, surveys of individuals involved in emergency recovery, such as medical personnel and affected individuals, provide valuable data for evaluating communication effectiveness, specialist training adequacy, and resource allocation. This approach also identifies problems in provision, logistics, and management.

Comparative analysis of experiences from different countries and regions enables adapting the best practices to specific conditions. International cooperation and knowledge exchange generate a global database that improves national response systems. Public education is also a critical area, which includes periodic educational events, training sessions, and awareness campaigns on first aid, evacuation procedures, and PPE use. These campaigns focus on vulnerable groups, such as children, older people, and people with disabilities. This decreases the risk of panic in a crisis.

Providing psychological support through assistance centers, hotlines, and stress management specialists can decrease anxiety and prevent post-traumatic stress disorder in the affected population and emergency responders.

Partnering with public and nonprofit organizations through social initiatives and volunteering increases the capacity of the healthcare system to perform evacuations, administer first aid, provide humanitarian aid, and establish temporary shelters. Finally, public confidence in government agencies and health services is critical for the system to function effectively at all levels. This can be achieved by transparently making decisions, providing timely information, and rapidly responding to emergencies.

ADDITIONAL INFO

Author contribution: Conceptualization and study design, data processing, sources review and writing of the original draft were carried out by a single author.

Funding sources: There was no funding for this work.

Conflict of interests: The author declares no explicit or potential conflicts of interests associated with the publication of this article.

Ethics approval: No ethics approval was required as the article represents a review.

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад автора. Концепция и дизайн исследования, обработка материала, обзор литературы и написание текста осуществлялись единственным автором.

Источник финансирования. Финансирование данной работы не проводилось.

Конфликт интересов. Автор декларирует отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Этическая экспертиза. Этическая экспертиза не проводилась, так как статья носит обзорный характер.

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