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Current State of Vaccine Prophylaxis and Its Resource Supply in the Post-Pandemic Period: a Review

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ABSTRACT

At present, the global community views vaccination as the most accessible and economically efficient infection control technology, a pathway to active longevity, and one of the most powerful public health tools with proven epidemiological effectiveness. The National Immunization Schedule (NIS) of the Russian Federation is constantly being improved in response to various challenges and changes in the epidemic situation. In recent years, the list of infections for which vaccines have been included in the NIS has expanded, including for epidemic indications; the vaccination strategy has changed in terms of expanding the indications for vaccination in the populations at risk. However, the existing system of vaccination coverage indicators in target groups does not allow for monitoring the timeliness of vaccination initiation, as it only considers those who have completed the immunization process. Vaccinations outside the target age groups do not ensure protection for infants, who are the most vulnerable to infection, and the catch-up and clean-up vaccination strategies do not quickly correct missed vaccination opportunities within the prescribed timelines, which has led to an unstable situation in recent years regarding several vaccine-preventable infections such as measles, pertussis, and mumps.

It should be noted that during the COVID-19 pandemic, the routine vaccination programs for children suffered significantly. A substantial disruption in immunization of varying degrees occurred in all regions monitored by the World Health Organization (WHO). As early as May 2020, in the first year of the pandemic, the WHO reported that at least 80 million children under the age of one year had missed vital vaccinations. The emerging problems can only be addressed promptly through the use of modern digital technologies, with the development of entirely new qualitative indicators for assessing the vaccination coverage of the pediatric population at all levels of outpatient care (local health districts, outpatient departments, ambulatory care centers) and educational institutions for children.

Lack of information on the timeliness of vaccination initiation in paper reports does not allow for prompt assessment and correction of the situation. The transition to digital technologies in vaccination reporting makes is possible to address these shortcomings in real time and implement corrective actions in a timely manner. Another key area in improving epidemiological surveillance of vaccine-preventable diseases is the assessment of the extent to which disease incidence and transmission rates in a given area depend on preventive vaccination coverage, as well as the monitoring of vaccine composition compatibility with the antigenic profiles of circulating genetic variants of pathogens—activities that require modern resource support.

Keywords: vaccination; vaccine hesitancy; immunization programs; vaccination coverage; review.

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Современное состояние вакцинопрофилактики и её ресурсное обеспечение в постпандемический период: научный обзор

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АННОТАЦИЯ

В настоящее время мировое сообщество рассматривает вакцинацию как наиболее доступную и экономически эффективную технологию борьбы с инфекциями, как путь к активному долголетию и как один из самых мощных инструментов общественного здравоохранения с доказанной эпидемиологической эффективностью. Национальный календарь профилактических прививок Российской Федерации постоянно совершенствуется с учётом вызовов времени и изменений в эпидемической ситуации. В последние годы расширился список инфекций, прививки против которых были включены в национальный календарь профилактических прививок, в том числе по эпидемическим показаниям; изменилась стратегия вакцинопрофилактики в части расширения показаний для прививок у контингента с рисками здоровью. Однако существующая система оценочных показателей привитости в индикаторных группах не позволяет контролировать своевременность начала прививок, так как учитывает только лиц, закончивших вакцинацию. Прививки вне декретированного возраста не позволяют обеспечить защиту детей раннего возраста, наиболее уязвимых к инфекции, а стратегии догоняющей (catch up) и подчищающей (clean up) вакцинации не позволяют оперативно скорректировать упущенные возможности для вакцинации в календарные сроки, что в последние годы привело к нестабильной ситуации по ряду прививаемых инфекций, таких как корь, коклюш, эпидемический паротит.

Следует констатировать, что во время пандемии COVID-19 система плановой вакцинации детей значительно пострадала. Существенный сбой в иммунизации произошёл во всех регионах, курируемых Всемирной организацией здравоохранения, хотя и в разной степени. Уже в мае 2020 года, т.е. в первый год пандемии, Всемирная организация здравоохранения сообщила о том, что по меньшей мере 80 млн детей в возрасте до 1 года пропустили жизненно важные прививки. Оперативно решить возникающие проблемы возможно только путём применения современных цифровых технологий с разработкой на их основе абсолютно новых качественных показателей оценки привитости детского населения на всех уровнях амбулаторной помощи (участок, отделение, поликлиника) и детских образовательных учреждений.

Отсутствие информации о своевременности начала вакцинации в отчётах на бумажных носителях не позволяет оперативно оценить и исправить ситуацию. Переход к цифровым технологиям в отчётности по прививкам позволяет устранить эти недостатки в реальном времени и своевременно включить коррекционные мероприятия. Другим направлением в совершенствовании эпидемиологического надзора за вакцинопрофилактикой являются оценка степени зависимости заболеваемости вакциноуправляемыми инфекциями на территории и уровня воспроизводства инфекции от полноты охвата профилактическими прививками, а также мониторинг соответствия состава вакцин антигенному профилю циркулирующих в популяции геновариантов возбудителей, что требует современного ресурсного обеспечения.

Ключевые слова: вакцинация; нерешительность в отношении вакцинации; программы иммунизации; охват вакцинацией; обзор.

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INTRODUCTION

Immunization is one of the most effective ways to fight infections, as evidenced by global practices. It is widely regarded as one of the greatest public health achievements of the 20th century. Owing to immunization, smallpox has been eradicated, and the prevalence of diphtheria, pertussis, poliomyelitis, measles, rubella, mumps, and hepatitis B has significantly decreased. Immunization remains relevant as local outbreaks and epidemics continue to emerge due to decreasing preventive vaccination coverage, vaccination schedule violations, and organizational defects, indicating the "vaccine dependence" of contemporary society [1]. The global community still considers vaccination the most accessible and cost-effective method for combating infections with various transmission mechanisms. Furthermore, it is considered a means of achieving active longevity and one of the most powerful public health tools with proven epidemiological efficiency [1–6]. Due to the peculiarities of the mechanism of pathogen transmission and the persistence of post-infection immunity, vaccination is the only method of controlling certain infections. Neonatal tetanus and poliomyelitis, for example, became controllable only after appropriate vaccines were used. Routine immunization is also the only measure for controlling measles and diphtheria [7]. Over the last 30 years, the number of vaccine-preventable infections has doubled [4, 8]. The cost-effectiveness of immunization is evident in the smallpox eradication program. The program cost $313 million, whereas the preventable damage would have cost up to $2 billion annually. According to the World Health Organization (WHO), immunization programs save more than six million children annually [9-11], including over half from measles, 1.2 million from neonatal tetanus, and 1.8 million from pertussis [12]. Years of experience with vaccines have confirmed the important role of prophylaxis in reducing the incidence of infections to sporadic levels. Through mass vaccination, the incidence of viral hepatitis B in Russia decreased from $8.6^{0}/_{0000}$ in 2005 to $0.35^{0}/_{0000}$ in 2020, whereas the incidence of rubella decreased from $100.8^{0}/_{0000}$ in 2005 to three cases in 2020 [1, 4, 12–14]. By 2018, the incidence of diphtheria decreased by 10,000-fold compared with the pre-vaccine period. The incidence of hepatitis A and B, pertussis, measles, and mumps decreased tenfold. No cases of paralytic poliomyelitis or tetanus were reported [15].

DATA SEARCH METHODOLOGY

Publications were searched for and selected using the PubMed and eLibrary.ru search engines and the CyberLeninka and SpringerLink databases. The search was limited to the period from 2019 to 2024 with a search depth of five years. The main areas of the scientific search were the immunoprophylaxis of infectious diseases and the epidemiological features of vaccine-preventable infections (e.g., tuberculosis, viral hepatitis B, diphtheria, tetanus, pertussis, measles, poliomyelitis, varicella, and HPV infection), postvaccinal complications, the organization of immunization, the national schedule of preventive vaccinations, adherence to vaccination by the population and health workers, reasons for refusing or not receiving vaccinations, and the role of health workers in fostering positive attitudes toward vaccination in the population. The following MeSH terms were used as a search query in foreign databases: vaccination OR acceptability OR adherence to vaccination OR covid-19 AND children. Abstracts, research protocols, clinical cases, and case series were not analyzed. English was set as the language restriction. Initial selection was based on the relevance of titles and abstracts to the search query, with duplicate publications excluded. The full-text analysis included 169 sources (66 Russian and 103 foreign), including monographs, manuals, dissertations, scientific publications in periodicals, open access publications from the WHO and the U.S. Centers for Disease Control and Prevention resources, as well as official regulatory documents.

IMMUNOPROPHYLAXIS AND ITS ROLE IN MANAGING EPIDEMICS OF INFECTIONS WITH DIFFERENT MECHANISMS OF TRANSMISSION

Immunization protects not only a specific individual (organismic level) from infection, but also ensures safety at the population level. At the organismic level, the criterion for determining the efficiency of vaccination is the quality of immunobiological preparations (IBPs) and the health status of the vaccinated individuals. At the population level, the criterion is controlling infections with different transmission mechanisms on a global scale. This depends directly on the timeliness and completeness of the population's vaccination coverage and the antigenic composition of vaccines aligning with the circulating pathogen genotypes in the territory. Previously, the main indicators of immunization program efficiency were considered to be reduced morbidity, less severe clinical manifestations, and fewer fatalities [1]. However, practical experience with immunization shows that these indicators are not reliable in cases of sporadic morbidity. Therefore, in current conditions, the focus is on achieving complete preventive vaccination coverage and population immunity.

Immunoprophylaxis reduces morbidity and mortality from infections and is essential for achieving active longevity. For example, influenza vaccination mitigates the risk of adverse outcomes in patients with chronic cardiovascular disease and circulatory disorders [16]. Vaccinology has provided new opportunities to prevent cancer, including cervical cancer, liver cirrhosis, and hepatocarcinoma following viral hepatitis B infection [4]. According to B.F. Semenov, an Academician of the Russian Academy of Sciences, given the achieved epidemiological well-being, preventive vaccinations for a number of vaccine-preventable infections will remain relevant in the current century [4, 17].

Currently, the WHO has identified several strategic directions for the development of immunization for the near and distant future. The priorities include promoting adherence to immunoprophylaxis worldwide, ensuring vaccine and vaccination accessibility, and providing preventive care to everyone. Other priorities include providing every resident with information about the value of preventive vaccination, ensuring reliable financing of immunization programs at the state level, developing new IBPs based on existing platforms, maintaining an uninterrupted supply of vaccines to regions, and continuing scientific research in the field of immunoprophylaxis for various diseases.[1], [2]

Scientific research evaluating the efficiency of individual IBPs in the control of infections under different immunization strategies (selective, mass, and routine) is invaluable for determining strategic directions in their development. For example, an encouraging study was conducted in Belgium to assess the efficiency of pneumococcal vaccination. The study revealed a decrease in invasive pneumococcal infections and a stabilization of the incidence rate, even with uneven distribution of incidence and pneumococcal serotypes circulating in different regions of the country, when using pneumococcal conjugate vaccines of different valencies [18]. Similar results were obtained when evaluating the efficiency of the routine human papillomavirus (HPV) vaccination [19], which is recommended by the WHO as an intervention with the highest level of evidence (1A). A study conducted in the United States showed that, even with low vaccination coverage among girls aged 13–17 (32%) years, the prevalence of HPV serotypes included in the 2010 vaccine decreased by more than half [19], prompting the expansion of the HPV immunization program in the country. Consequently, the HPV vaccination coverage rate among 15-year-old girls in the United States surpassed 80% by early 2024.[3] In Australia, the HPV vaccination program for adolescents from 2007 to 2011 reduced the incidence of anogenital warts by 93% in girls under 21 years of age and by 73% in women under 30 years of age [19, 20]. In Sweden, the vaccination of over 2 million girls and women aged 10–44 years with the triple HPV vaccine between 2006 and 2010 reduced the incidence of condylomata acuminata by 76% [19, 21]. In 2020, Sweden published the first data on the efficiency of the HPV vaccine in preventing cervical cancer. Among girls and women under 31 years of age, only 19 cases of cervical cancer were diagnosed in those who received the quadrivalent HPV vaccine, compared with 538 cases in those who were not vaccinated. The cumulative incidence of cervical cancer was 47 cases per 100,000 vaccinated women and 94 cases per 100,000 unvaccinated women. After adjusting for age at follow-up, the incidence rate ratio comparing the vaccinated with the unvaccinated was 0.51 (95% confidence interval [CI]: 0.32–0.82). After adjusting for additional covariates, the ratio was 0.37 (95% CI: 0.21–0.57). After adjusting for all covariates, the incidence rate ratio was 0.12 (95% CI: 0.00–0.34) among women vaccinated before the age of 17 and 0.47 (95% CI: 0.27–0.75) among those vaccinated between 17 and 30 years of age [5]. This study exemplifies a scientific analysis of current infection control possibilities with IBPs.

Therefore, the importance of immunoprophylaxis in managing epidemics with different transmission mechanisms cannot be overstated, particularly when vaccination serves as the only means of infection control.

NATIONAL SCHEDULE OF PREVENTIVE VACCINATIONS AND PROSPECTS FOR ITS IMPROVEMENT IN THE PRESENT CONTEXT

Immunization was first implemented globally in 1974 as part of the WHO Expanded Program on Immunization. Under this initiative, vaccination against six infections—tuberculosis, diphtheria, pertussis, tetanus, poliomyelitis, and measles—became mandatory for children. Consequently, 80% of children worldwide were immunized against these infections by 1990 [22, 23]. Although vaccination coverage in Russia was significantly higher than the benchmarks, the problem was that the higher rates were obtained outside the ages decreed by the national vaccination schedule. This made young children vulnerable to vaccine-preventable infections.

The National Immunization Schedule (NIS) is a legal document that establishes the timing and procedure for preventive vaccinations in various countries, including Russia. It is based on WHO recommendations and the epidemiological situation of specific infectious diseases in the country. In 1997, the NIS mandated vaccinations against nine infections. In 2006, influenza vaccination was added to the list of mandatory vaccinations. In 2014, the list was updated to include vaccinations against Hemophilus influenzae infection for high-risk groups and pneumococcal infection.

The NIS is undergoing continuous improvement through the expansion of preventable infections and the introduction of new immunization programs. For example, the recommendations for the Hemophilus influenzae vaccine were extended beyond high-risk groups in 2021. Additionally,

[1] World Health Organization [Internet]. Guidance on Routine Immunization Services During the COVID-19 Pandemic in the WHO European Region. March 20, 2020. Available at: https://www.who.int/europe/ru/publications/i/item/WHO-EURO-2020-1059-40805-55114 Accessed on: January, 13, 2025.

[2] World Health Organization [Internet]. UNICEF and WHO warn of perfect storm of conditions for measles outbreaks, affecting children [cited 2022 April 27]. Available at: https://www.who.int/news/item/27-04-2022-unicef-and-who-warn-of--perfect-storm--of-conditions-for-measles-outbreaks--affecting-children Accessed on: January 13, 2025.

[3] World Health Organization [Internet]. Human Papillomavirus (HPV) vaccination coverage. Available at: https://immunizationdata.who.int/pages/coverage/hpv.html?CODE=RUS+USA&ANTIGEN=&YEAR= Accessed on: January 13, 2025.

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the BCG-M vaccination contingent (a tuberculosis vaccine for gentle primary immunization) was adjusted, and the third polio vaccination was moved to ages 6–7.[4] To prevent vaccine-associated paralytic poliomyelitis, an inactivated poliovirus vaccine was used for the vaccination and the first booster, whereas the trivalent live poliovirus vaccine was replaced with a bivalent vaccine. Groups to be vaccinated against influenza were expanded to include pregnant women and individuals entering military service. Recommendations were made for influenza vaccines containing relevant Russian antigens and for preservative-free vaccines to immunize children under one year of age and pregnant women. In accordance with international practices, priorities have been established for the use of combination vaccines and the optimization of vaccination schedules by shortening the intervals between inactivated vaccine administrations, as well as between inactivated and live vaccines.[5]

Considering the significant size of Russia and the varying epidemic situations of vaccine-preventable infections in different regions, Russian legislation does not preclude the development of regional preventive vaccination schedules [2]. These schedules may include vaccinations against infections that are not present in the NIS, such as rotavirus, meningococcal disease, and human papillomavirus infection. Additionally, varicella is included as one of the most difficult infections to control. This allows the regional schedules to be considered as a stage for the subsequent inclusion of these vaccinations in the NIS. The regional schedule of preventive vaccinations in the Sverdlovsk Region, for example, includes vaccinations against meningococcal infection, varicella, tick-borne viral encephalitis, and hepatitis A. The Chelyabinsk Region uses monoclonal antibodies for passive immunization against respiratory syncytial virus infection [24]. The Moscow regional preventive vaccination schedule includes additional vaccinations for children aged 3–6 entering preschool, including vaccinations against rotavirus, varicella, meningococcal infection, and viral hepatitis A. It also includes vaccinations against papillomavirus for girls aged 12–13 and a pertussis booster shot with acellular vaccine for children aged 6–7. In accordance with the Order of the Moscow Department of Health,[6] children in risk groups in Moscow, such as premature babies and those with congenital heart defects or other organ defects, are protected from respiratory syncytial virus infection using monoclonal antibodies. Thus, regional schedules of prophylactic vaccinations allow for the development of experience in controlling certain infections, which may later be implemented in other regions of the Russian Federation.

The feasibility of introducing each new vaccination into the NIS must be proven. For example, the argument for a rotavirus vaccine is the significant morbidity and viral transmission among young children, including during the newborn period. There is also a significant proportion of severe clinical cases with fatal outcomes. Additionally, there is a lack of effective etiological therapy, a low infectious dose, and an inability to ensure the complete safety of drinking water through virus control. According to the WHO, children under 5 years of age contract the rotavirus infection at least three times, and any of these episodes may be fatal. In Russia, rotavirus accounts for 49% of acute intestinal infections in children under 5 years of age, and the virus is prevalent among young children, ranging from 1.5% to 9%. This includes 71% of newborns who are virus carriers [4, 25, 26]. Controlled epidemiological studies conducted in recent years in several regions of the Russian Federation (Sverdlovsk, Tyumen, and the Moscow Regions) have confirmed the high efficiency of rotavirus vaccination among young children [27]. For example, a 7-year routine vaccination program against rotavirus infection for children in their first year of life in Podolsk (Moscow Region) demonstrated the following: a 51-fold decrease in the incidence of rotavirus gastroenteritis among children under 2 years of age, a 27-fold decrease among 3–6-year-olds, and a 43.3-fold decrease in hospitalizations of children with acute intestinal infections [27].

The situation with meningococcal infections may be similarly indicative. From 2017 to 2019, there was a steady decline in the incidence of generalized forms of meningococcal infection in Russia. The isolation and restriction measures introduced during the 2020 pandemic of the new coronavirus (COVID-19) led to an even greater decrease in the number of cases, down to 0.26 per 100,000 people [27]. However, the incidence of generalized forms of meningococcal infection increased twofold in 2022 compared with 2021. This requires addressing the need for routine vaccination of children and persons at risk of the disease using advanced vaccines that match the serotype characteristics of circulating genovariants of the pathogen [27].

Varicella is another problematic infection. In 2022, it ranked second among infectious diseases in Russia in terms of economic losses [27]. Universal vaccination of children to prevent varicella has been recognized worldwide. Japan developed the first live attenuated varicella vaccine in 1974. The vaccine strain of the virus was isolated from a child

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[4] Order of the Ministry of Health of the Russian Federation of December 06, 2021, No. 1122n, On Approval of the National Schedule of Prophylactic Vaccinations, the Schedule of Prophylactic Vaccinations for Epidemic Indications, and the Procedure for Prophylactic Vaccinations. Available at: https://base.garant.ru/403258640 Accessed on: January 13, 2025.

[5] Letter of the Ministry of Health of the Russian Federation of January 21, 2022, No. 15-2/I/2-806, On Sending Methodological Recommendations on Preventive Vaccinations in Accordance with Order of the Ministry of Health of the Russian Federation of December 06, 2021, No. 1122n, On Approval of the National Schedule of Prophylactic Vaccinations, the Schedule of Prophylactic Vaccinations for Epidemic Indications, and the Procedure for Prophylactic Vaccinations. Available at: https://base.garant.ru/403481186 Accessed on: January 13, 2025.

[6] Order of the Moscow City Health Department of December 25, 2024, No. 4491-r, On Measures Aimed at Off-Season Prevention of Respiratory Syncytial Virus Infection in Children in Moscow at the Expense of the Moscow City Budget. Available at: https://base.garant.ru/411233263/?ysclid=m831gpxg7k870301311 Accessed on: January 13, 2025.

with varicella. It was then attenuated and is now used to produce licensed varicella vaccines worldwide. A major breakthrough in vaccinology occurred when the vaccine was combined with a three-component measles, rubella, and mumps (MMR) vaccine, resulting in a quadrivalent MMR-V vaccine [5]. Several countries in Europe and the United States currently administer scheduled vaccinations against varicella. However, the infection cannot be eradicated because the virus persists in the spinal ganglia of the peripheral nervous system throughout life. There is also a risk of recurrent infection in immunocompromised populations in the form of *herpes zoster*. Furthermore, reactivation of the varicella-zoster virus in herpes zoster may lead to transmission to susceptible populations, making eradication of the infection impossible [5]. Nevertheless, the United States has accumulated positive experience with mass vaccination against varicella. Routine immunization for 15 years has resulted in a 90% to 95% reduction in varicella incidence, affecting not only the vaccinated population, but also the unvaccinated. This reduction is due to a decrease in "effective contacts" for pathogen transmission and the population-level effects of vaccination. Furthermore, the implementation of varicella prevention programs has reduced varicella-related hospitalizations by 90%. The estimated efficiency of the vaccination, even with a single dose, ranged from 73% to 90% during the project [5]. Germany was one of the first countries in Europe to introduce universal immunization against varicella and establish a surveillance system for this infection. An analysis of vaccination efficiency in this country showed that, according to two independent studies [5, 28], the incidence of varicella in children under 19 years of age decreased by 76%–84% in the first years after the start of mass vaccination (2004). The hospitalization rate decreased by 60% in children and 40% in adults between 2005 and 2012. Overall, the efficiency of the varicella vaccine in preventing the disease was 86% after one dose and 94% after two doses. By December 2020, Germany, Austria, Finland, Greece, Luxembourg, and parts of Italy and Spain had introduced varicella vaccination programs at the national level. Therefore, 16 countries in the European Region currently recommend vaccination for adolescents and/or children at risk, 13 recommend vaccination for healthcare professionals, and 4 recommend vaccination for preschool education personnel [5]. In Russia, the question of including varicella vaccination in the NIS remains unresolved due to the lack of a national vaccine. Regarding herpes zoster, there is currently no convincing evidence that varicella vaccination affects its incidence in unvaccinated populations [29]. This issue may only be resolved through analytical epidemiological studies with a high level of evidence.

Another relevant infection is pertussis. Despite high vaccination coverage in Russia in recent years, the incidence of this infection has increased. In 2018, the number of pertussis cases increased 1.9-fold compared with 2017, with more than 90% of cases occurring in children under 14 years of age [30]. In Russian and foreign studies, the main cause of pertussis morbidity in previously vaccinated children is considered to be a decrease in post-vaccination immunity over time. In Moscow, 57% of children aged 7–14 who contracted pertussis were fully immunized at the prescribed age. Among children aged 3–6, this figure ranged from 24% to 37% [31]. The peculiarities of the age distribution of patients, the challenges of the clinical and laboratory diagnosis of pertussis, and the decrease in post-vaccination immunity two years after the first booster shot necessitate the inclusion of a booster immunization in the NIS. For example, this immunization could be administered at 6–7 years of age [32]. Importantly, the WHO still only recommends whole-cell pertussis vaccines (e.g., adsorbed diphtheria-tetanus-pertussis [DTP] vaccine) for initial immunization and the first booster shot against pertussis. However, most countries use vaccines with an acellular pertussis component for booster immunization at 6–7 years of age, and the age for booster immunization varies geographically. For example, Brazil administers booster vaccinations at 3–4 years of age, whereas Austria, Belgium, and Hungary perform boosters at 5–6 years of age. In Italy and Belgium, adolescents and adults receive routine vaccinations every 10 years. In Italy, Spain, Belgium, and other countries, however, routine vaccinations are exclusively administered to pregnant women [24]. In 2019, the Russian Federation approved the use of Adacel, a combined adsorbed diphtheria vaccine with reduced tetanus antigen content and an acellular pertussis component, for booster immunization against pertussis, diphtheria, and tetanus in individuals aged 4 to 64 years. That same year, Moscow and Yekaterinburg included a second pertussis booster shot for children aged 6–7 years in their preventive vaccination schedules. However, the use of a new, complex vaccine for booster shots at 14 years of age, for pregnant women, and for adults in contact with infected family members (cocooning) remains relevant. The most severe forms of infection occur in children under one year of age, especially during the first six months of life, as well as in newborns. These children are usually infected by their mother or other children in the family. Previous studies have shown that severe pertussis infections occur four times more frequently in unvaccinated children than in those vaccinated. The risk of residual central nervous system effects after severe infection is 1.8 per 1000 patients [33]. Recently, evidence has emerged suggesting that non-vaccine variants of *Bordetella pertussis* are increasingly prevalent in pertussis infections and are gradually replacing vaccine strains in the population [34]. Further study of such materials using molecular genetic methods is required.

Thus, the NIS is a "living organism" that must be updated constantly according to the general and territorial-specific epidemic situation of the infection. Improving the NIS is an integral part of the vaccine-preventable disease (VPD) surveillance. This improvement should be accompanied by constant updates to the regulatory framework, the development and introduction of new IBPs, and increased funding for vaccine production enterprises and scientific research. These changes will optimize the vaccination schedules.

EXISTING SYSTEM OF VACCINE-PREVENTABLE DISEASE SURVEILLANCE AND ITS RESOURCE SUPPLY

To effectively manage immunization as a real-time activity, a systematic approach to its optimization is necessary. This approach should utilize new indicators to assess documented vaccination and population protection. Contemporary capabilities, including digital technologies and artificial intelligence, are valuable resources in this regard. In the context of a challenging epidemiological situation and the necessity of counteracting anti-vaccination sentiments, the population aspects of immunization are of particular relevance.

As before, one aspect of VPD surveillance involves analyzing the completeness of preventive vaccination coverage and rates among indicator groups [1]. However, the existing system does not allow for the assessment of the timeliness of the start of vaccination. This prevents real-time monitoring of the effectiveness of medical organizations in implementing vaccination schedules. While the assessment of documented vaccination is relatively straightforward, the results are arbitrary when it comes to evaluating individual or population-level protection. This is because they do not reflect the actual level of protection against infection, either for an individual or for the population. Research conducted on diphtheria and measles infection models has demonstrated that the concepts of "vaccinated" and "protected" do not always align [3].

In contemporary circumstances, the development of new qualitative indicators to assess the vaccination of the child population at different outpatient care levels (local health districts, outpatient departments, and ambulatory care centers) and in children's educational institutions using existing digital technologies minimizes the inevitable distortion of documentary data that occurs when preparing paper reports. In conditions of an unstable epidemic situation involving several vaccine-preventable infections, it is important to study how the incidence of these infections in a given territory depends on the completeness of preventive vaccination coverage. Furthermore, it is crucial to continuously monitor population protection levels and study how well the composition of vaccines aligns with the antigenic profile of circulating pathogen variants in the population. This requires contemporary resource provision strategies.

The Epidemiology Department at Perm State Medical University named after Academician E.A. Wagner (I.V. Feldblum, 1994) developed the concept of regional management of immunization. The concept was enshrined in the Perm Region Law on Immunization of Infectious Diseases in 1997 and was implemented at the managerial and territorial levels.

VPD surveillance involves monitoring indicators that characterize its status as an intervention. This allows for the timely identification of organizational defects in vaccination, and enables the implementation of management decisions to eliminate deficiencies and change immunization strategies, ensuring the flexibility of the vaccination schedules [1, 3]. The ultimate goal of VPD surveillance is to proactively impact morbidity by managing immunization as an intervention at the population level [1, 3].

VPD surveillance consists of three subsystems: informational, diagnostic, and managerial. The informational subsystem collects data on immunization as an intervention. This subsystem includes an assessment of the population's documented vaccinations, monitoring of immunological efficiency by studying the population's overall immunostructure and the intensity of immunity in high-risk and indicator groups, and the correct selection of children for vaccination, followed by an assessment of adverse events after immunization, their structure, and the causes of their occurrence. It also ensures the quality of vaccines and compliance with the "cold chain" requirements. However, the VPD surveillance informational subsystem lacked control over the timeliness of vaccinations within the prescribed calendar dates. This was not included in the existing accounting and reporting documents. The transition to digital technologies instead of paper-based reports enables the timely receipt of information on the start of vaccinations and subsequent scheduling. This new resource enables the assessment of vaccinations within the VPD surveillance informational subsystem. The importance of this assessment in the diagnostic subsystem of VPD surveillance has yet to be determined. Chernova et al. [35, 36] believe that timely vaccination is a key indicator of NIS implementation. Delayed immunization leads to further violations of the vaccination schedule, an increased risk of disease at an early age, and possible adverse outcomes. However, existing vaccination record-keeping and reporting forms do not require information on the timeliness of vaccination initiation or the assessment of vaccination in cohorts of children at risk for health problems, including prematurity [37, 38]. For example, no studies have shown that children born with extremely low or very low birth weights were promptly vaccinated [37].

The diagnostic subsystem of epidemiological surveillance involves making an epidemiological diagnosis of the state of immunization. This subsystem identifies infections with low-quality and ineffective immunization indicators and determines the territories, medical organizations, and local health districts that require corrective measures [3]. For the epidemiological surveillance system to function successfully, new information technologies must be used. This includes developing and introducing new software products for the Federal Service for Surveillance on Consumer Rights

Protection and Human Wellbeing, as well as healthcare institutions. It also includes optimizing preventive vaccination record-keeping and reporting forms, and using new indicators to assess vaccine prevention efforts.

APPROACHES TO THE ORGANIZATION OF IMMUNIZATION IN THE POST-PANDEMIC PERIOD

The state health policy of the Russian Federation prioritizes preserving the nation's health, reducing morbidity and mortality, and increasing life expectancy[7] [22]. Mass immunization provides the most effective protection against infectious diseases while making the best use of available economic resources [22, 39]. The preventive aspect of modern public healthcare contributes to achieving the set goals of preventing infectious diseases in various population groups and creating safe environmental conditions. Furthermore, it contributes to the upbringing, education, and professional activities of the inhabitants of our country [22, 40].

The routine childhood immunization system was severely impacted worldwide during the pandemic. In May 2020, the WHO reported that at least 80 million children under one year of age had missed essential immunizations[8] [41] and that 23 million children had not received routine immunizations, which was 3.7 million more than in 2019.[9] According to model estimates, more than 8 million children did not receive the third dose of the DTaP vaccine or the first measles vaccination in 2020 [42]. The largest decline in preventive vaccination coverage occurred in April 2020, with 33% fewer children receiving the third DTaP vaccine dose (ranging from 9% in the WHO African Region to 57% in the South American Region) [43]. The missed vaccination opportunities associated with the pandemic have jeopardized the success of previous immunoprophylaxis efforts, which has serious implications for the international community's efforts to eradicate and eliminate VPDs. The challenge lies in obtaining accurate and systematic measurements of these changes in the global immunization system. Several publications and guidelines have appeared on avoiding vaccination cessation during the COVID-19 pandemic[1] [41].

As early as 2022, the WHO initiated a study in the United States to assess the extent of immunization disruption in 170 countries worldwide [43]. The final document noted significant pandemic-related immunization failures in all WHO regions. The main causes were interruptions in routine vaccination, reduced availability of health services, disruptions in vaccine supply, and reduced demand for immunization services [43]. These shortcomings resulted in an increased number of unvaccinated children, which led to a destabilization of the situation with respect to vaccine-preventable infections (particularly measles and pertussis), subsequently increasing mortality rates [43].

Experts have expressed particular concern regarding the curtailment of polio and measles eradication programs, which has resulted in an elevated risk of the reemergence of these infections[10] [43–47]. The persistence of poliomyelitis in Pakistan and Afghanistan, coupled with the growing circulation of vaccine-derived poliovirus, is a warning to intensify international efforts to control the infection [43].

Six WHO regions committed to eliminating measles infections by 2020. However, only one region, the Americas, achieved this goal by 2016. After initially eliminating the disease, other countries, including Venezuela (in 2018), Brazil (in 2019), and Russia (in 2024), subsequently re-established endemic transmission of measles [7, 48]. Since 2017, low adherence to immunization has resulted in measles vaccination coverage rates worldwide that no longer reach the levels necessary to eliminate the infection. This has resulted in the highest number of reported deaths from measles in two decades [49]. Experience from previous epidemics, such as the 2014–2015 Ebola outbreak in West Africa, has shown that suspending vaccination programs and reducing measles vaccination coverage resulted in more measles deaths than Ebola deaths in that country. This underscores the importance of maintaining vaccination programs, even during crisis situations [43, 50]. Currently, the incidence of measles varies greatly between countries and WHO regions, but the need to strengthen control of this infection worldwide is evident.

The COVID-19 pandemic has affected the epidemiological surveillance system for many infectious diseases. Failures in monitoring circulating strains of pathogens for most infectious diseases have greatly reduced the number of clinical specimens available for laboratory testing, resulting in limited information on circulating pathogen genotypes, such as the measles virus genotype [7].

During the COVID-19 pandemic, in many countries, misinformation about the ineffectiveness of vaccines caused uncertainty among parents regarding the necessity of vaccinations, particularly those requiring multiple

[7] Decree of the President of the Russian Federation of May 07, 2018, No. 204, On National Goals and Strategic Objectives for the Development of the Russian Federation for the Period Until 2024. Available at: http://www.kremlin.ru/acts/bank/43027 Accessed on: January 13, 2025.

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doses[2] [51, 52]. According to the WHO and United Nations International Children's Emergency Fund, the proportion of children who received their first measles and rubella vaccination decreased from 95% in 2019 to 87% in 2021. Meanwhile, the number of children who were not vaccinated against diphtheria, pertussis, and tetanus increased from 10% in 2019 to 26% in 2021[2]. This situation endangers not only the pediatric population, but also the general population. It increases susceptibility to infectious diseases and the likelihood of their spread [52].

Thus, existing problems with the organization of immunoprophylaxis during the COVID-19 pandemic were exacerbated in the post-pandemic period. Moreover, disruptions in vaccine supply, reduced access to health services, and insufficient crisis preparedness of health systems affected the timeliness of routine immunizations. Misinformation and decreased public confidence in immunoprophylaxis have exacerbated these problems. An analysis of the impact of the COVID-19 pandemic reveals that immunization programs must be continuous and constantly improved, even during crises, to achieve the ultimate goal of immunization: the elimination and eradication of certain infections in the future.

CONCLUSION

Immunoprophylaxis is one of the most powerful and cost-effective public health tools. Advances in vaccinology and new vaccine technologies based on both established and novel platforms expand opportunities for vaccination and provide protection to people of all ages. Vaccines protect the vaccinated against specific pathogens or infections. Additionally, they have the potential to protect the unvaccinated by reducing effective contacts with pathogens in the immune population. Research shows that certain vaccines may protect against diseases other than those for which they were originally designed, thanks to a phenomenon known as heterologous effects.

The development of qualitative assessment indicators of childhood vaccination at different levels of outpatient care (local health districts, outpatient departments, and ambulatory care centers), as well as at children's educational institutions, based on existing digital technologies, will minimize the risks of data distortion that inevitably arise when reports are generated on paper.

An equally important aspect of VPD surveillance is establishing a correlation between the morbidity level of a particular infection and the completeness of preventive vaccination coverage among specific age groups and populations. This also involves monitoring compliance with the antigenic profile of the vaccine composition and the sero- and genovariants of the circulating pathogen, which requires constant IBPs adjustments.

The key to effectively implement the vaccination schedule is to ensure adherence by parents and healthcare providers and to overcome communication risks.

ADDITIONAL INFORMATION

Authors' contribution. V.A. Minaeva—collection and analysis of literary data, writing and editing the text of the article; A.A. Golubkova—analysis of literary data, editing the article. Thereby, all authors provided approval of the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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