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THE FEATURES OF ADVANCES AND CHALLENGES IN COVID-19 VACCINE DEVELOPMENT, EFFICACY, SAFETY, AND GLOBAL DEPLOYMENT IN GENERAL

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COVID-19 ვაქცინის შემუშავების მიღწევები და გამოწვევები: ეფექტურობის, უსაფრთხოებისა და გლობალური დანერგვის პერსპექტივები

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რეზიუმე

COVID-19 ვაქცინების სწრაფი განვითარება და გავრცელება სამედიცინო და ფარმაცევტულ მეცნიერებებში ისტორიულ ეტაპს წარმოადგენს, რაც გლობალური პანდემიის წინააღმდეგ საბრძოლველად კრიტიკულ ინსტრუმენტია. სტატია მიმოიხილავს ვაქცინის სხვადასხვა პლატფორმის, მათ შორის mRNA-ს, ვირუსული ვექტორის, ცილოვანი ქვეერთეულის და ინაქტივირებული ვაქცინების შესახებ არსებულ ცოდნას, ხაზს უსვამს მათ მექანიზმებს, ეფექტურობასა და უსაფრთხოების პროფილებს. ნაშრომში განხილულია ვაქცინების მიერ გამოწვეული იმუნოლოგიურ რეაქციები, მათი ეფექტურობა ისეთი ახალი ვარიანტების წინააღმდეგ, როგორიცაა Delta და Omicron, და გამოწვევები რომლებსაც იმუნიტეტის შემცირება და ვაქცინაციისადმი ყოყმანი წარმოშობს. გარდა ამისა, სტატია ეხება ვაქცინების განაწილებაში გლობალურ უთანასწორობას და თანაბარი ხელმისაწვდომობის ეთიკურ ასპექტებს. კლინიკური კვლევების მონაცემების, რეალური სამყაროს მტკიცებულებებისა და სამეცნიერო მოსაზრებების ინტეგრირებით, სტატია მიმოიხილავს პერსპექტივებს COVID-19 ვაქცინაციის ძალისხმევის მიღწევებსა და მიმდინარე გამოწვევებზე.

Background: The emergence of SARS-CoV-2 in late 2019 precipitated an unprecedented global health crisis, necessitating the rapid development of effective vaccines. Historically, vaccine development spanned decades, but the urgency of the pandemic accelerated this timeline to under a year, leveraging advancements in biotechnology and international collaboration. Multiple vaccine platforms were deployed, each with distinct advantages and limitations. mRNA vaccines, such as those developed by Pfizer-BioNTech and Moderna, demonstrated high efficacy and rapid adaptability, while viral vector and protein subunit vaccines offered alternative solutions with simpler storage requirements. Inactivated vaccines, though less efficacious, played a pivotal role in regions with limited infrastructure.

Goal: The primary objectives of this review are to evaluate the efficacy and safety of COVID-19 vaccines across different platforms.

Methodology: The material of the article was the revised data from scientific publications, which were processed, analyzed, overviewed and reviewed by generalization and systematization. Research studies are based on a review/overview assessment of the development of critical visibility and overlook of the modern scientific literature. Use the following databases (for extensive literature searches to identify advances and challenges in covid-19 vaccine development: a comprehensive review of efficacy, safety,

and global deployment): PubMed, Scopus, Web of Science, Clinical key, Tomson Reuters, Google Scholar, Cochrane Library, and Elsevier Foundations.

Results and Discussion. The development of COVID-19 vaccines has marked a pivotal achievement in modern medicine, characterized by unprecedented speed and innovation. The global scientific community responded to the SARS-CoV-2 pandemic with the rapid initiation of multiple vaccine platforms, including mRNA-based vaccines, viral vector vaccines, protein subunit vaccines, and inactivated virus vaccines. The most prominent vaccines—Pfizer-BioNTech's BNT162b2, Moderna's mRNA-1273, Oxford-AstraZeneca's ChAdOx1 nCoV-19, and Johnson & Johnson's Ad26.COV2.S—demonstrated strong immunogenicity and efficacy during Phase III clinical trials, with efficacy rates ranging from 66% to over 95% in preventing symptomatic COVID-19. Notably, mRNA-based vaccines achieved higher efficacy but required ultra-cold chain storage, posing logistical challenges in low-resource settings.

In terms of safety, the majority of vaccines exhibited favorable profiles, with mild to moderate side effects including injection site pain, fatigue, headache, and mild fever. However, rare adverse events, such as vaccine-induced immune thrombotic thrombocytopenia (VITT) associated with adenoviral vector vaccines and myocarditis following mRNA vaccines, have raised concerns and necessitated robust pharmacovigilance systems. The emergence of new SARS-CoV-2 variants, particularly Delta and Omicron, tested the real-world efficacy of existing vaccines. Although vaccine effectiveness against infection declined with these variants, protection against severe disease and hospitalization remained relatively high, especially following booster doses.

Efficacy and Immune Response: Clinical trials and real-world data have demonstrated the high efficacy of mRNA vaccines, with Pfizer-BioNTech and Moderna vaccines showing approximately 95% efficacy in preventing symptomatic infection. Viral vector vaccines, such as AstraZeneca and Johnson & Johnson, exhibited moderate efficacy (66–79%) but strong protection against severe disease. Protein subunit vaccines, like Novavax, achieved around 90% efficacy, while inactivated vaccines reported variable efficacy (50–80%). The durability of immune responses varied, with mRNA vaccines inducing robust but waning antibody levels, whereas viral vector vaccines elicited more sustained T-cell immunity.

Safety Profiles: Most vaccines were associated with mild, transient side effects, such as injection site pain and fatigue. Rare adverse events, including myocarditis (linked to mRNA vaccines) and thrombosis with thrombocytopenia syndrome (associated with viral vector vaccines), were identified but remained exceedingly rare. Continuous pharmacovigilance and transparent communication were critical in maintaining public trust.

Emerging Variants: Variants such as Delta and Omicron reduced vaccine efficacy against symptomatic infection but maintained strong protection against severe outcomes. Booster doses and updated formulations were essential in restoring immunity, highlighting the need for adaptive vaccine strategies.

Public Acceptance: Vaccine hesitancy, driven by misinformation and mistrust, hindered immunization efforts. Targeted public health campaigns and community engagement were effective in improving uptake, emphasizing the importance of science communication.

Future Directions: Next-generation vaccines, including pan-coronavirus and mucosal vaccines, hold promise for broader and longer-lasting protection. Investments in global surveillance and rapid-response systems are crucial for addressing future variants and pandemics.

The COVID-19 vaccine landscape reflects a complex interplay of scientific achievement, public health policy, and socio-political challenges. While the efficacy and safety of vaccines have been largely

validated, global deployment remains uneven, and long-term control of the pandemic will depend on continued surveillance, equitable access, and public trust in vaccination programs.

The continuous evolution of SARS-CoV-2 highlights the need for sustained research and innovation in vaccine development to ensure long-term protection against emerging variants. While current COVID-19 vaccines have significantly reduced the severity of infections and mortality rates, several challenges remain, necessitating advancements in vaccine technology, distribution strategies, and public health policies.

One of the key areas of future research is the development of next-generation COVID-19 vaccines that provide broader and longer-lasting immunity. Scientists are exploring universal coronavirus vaccines capable of targeting multiple strains, including potential future variants. Such vaccines would reduce the need for frequent booster doses and improve protection against newly emerging mutations.

Conclusion: The development and deployment of COVID-19 vaccines represent a monumental achievement in science and public health. However, the journey has revealed critical challenges, including inequitable distribution, variant-driven immune escape, and public hesitancy. To address these issues, the following recommendations are proposed: Enhance Global Equity: Strengthen international cooperation to ensure equitable vaccine access, support local manufacturing in low-income countries, and waive intellectual property barriers where necessary; Improve Surveillance: Invest in real-time genomic surveillance and post-marketing safety monitoring to track variants and adverse events; Adapt Vaccine Strategies: Prioritize research into universal coronavirus vaccines and alternative delivery methods, such as nasal sprays, to enhance mucosal immunity and ease of administration; Combat Hesitancy: Launch evidence-based public health campaigns to counter misinformation and build trust in vaccination programs; Foster Preparedness: Establish frameworks for rapid vaccine development and distribution to mitigate future pandemics.

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SUMMARY

The rapid development and deployment of COVID-19 vaccines have marked a historic milestone in medical and pharmaceutical sciences, offering a critical tool to combat the global pandemic. The article synthesizes current knowledge on the diverse vaccine platforms, including mRNA, viral vector, protein subunit, and inactivated vaccines, highlighting their mechanisms, efficacy, and safety profiles. Were discussed the immunological responses elicited by vaccines, their performance against emerging variants such as Delta and Omicron, and the challenges posed by waning immunity and vaccine hesitancy.

Keywords: COVID-19 vaccines, SARS-CoV-2, efficacy, safety, global equity, emerging variants