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mRNA VACCINES AND THEIR ROLE IN IMMUNIZATION AGAINST INFECTIOUS DISEASES: ADVANCES, CHALLENGES AND FUTURE PROSPECTS

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Abstract: Objective: To analyze the potential of mRNA vaccines in the fight against emerging infectious diseases. **Methodology:** The literature review was conducted based on the PVO strategy, formulating the question: "What is the potential of mRNA vaccines in the development of effective and safe immunizations against infectious diseases?". The searches were carried out on the PubMed-MEDLINE database, using the terms: ("mRNA vaccines") AND ("infectious diseases") AND ("vaccine development"). After applying inclusion and exclusion criteria, 27 articles were selected for analysis. **Discussion**: mRNA vaccines, such as those from Pfizer-BioNTech and Moderna, have demonstrated efficacy of more than 90% against COVID-19, providing robust protection against serious infections and stimulating long-lasting immunological memory. This technology also stands out for its potential to combat other emerging pathogens, including influenza, Zika and HIV. In addition, mRNA vaccines are being explored for the development of personalized immunizations in the treatment of cancer. Despite challenges such as RNA stability and accessibility issues, technological advances, including self-amplifying mRNA, optimized delivery systems and lipid nanoparticles, have increased the efficacy and viability of these vaccines, enabling new immunization strategies and personalized therapies. **Final considerations**: mRNA vaccines have emerged as an innovative approach to fighting infectious diseases, showing high efficacy and safety, especially in the context of COVID-19. Advances such as self-amplifying mRNA and improvements in RNA stability reinforce the potential of these vaccines to tackle challenges such as HIV and cancer. Despite the limitations, ongoing research promises to expand the applications of this technology, offering a promising future in the prevention and treatment of a wide range of infectious and chronic diseases.

Keywords: mRNA vaccines, immunization, emerging infectious diseases, mRNA technology, therapeutic vaccines.

INTRODUCTION

Vaccination represents one of the most significant advances in the history of medicine, playing a crucial role in the prevention and control of numerous infectious diseases (Yılmaz *et al.*, 2021). With the progress of biotechnology, messenger RNA (mRNA) vaccines have emerged as an innovative approach, offering substantial advantages over traditional vaccines. These vaccines can be developed rapidly from linearized plasmid DNA or by in vitro transcription based on the polymerase chain reaction (Schmidt & Schnierle, 2023). In addition to their effectiveness in protecting against viral infections, mRNA vaccines have promising potential for applications in oncology, allowing for a robust and highly specific immune response (Xu, Yang, Li & Zhang, 2020). In addition, their versatility makes it possible to encode multiple antigens in a single formulation, promoting broader immunization against different pathogens or viral variants (Chaudhary, Weissman & Whitehead, 2021).

The rapid development of mRNA vaccines against COVID-19 has highlighted their potential to transform global immunization, enabling an efficient and record-time response to health emergencies (Aljabali *et al*., 2023). WHO data indicate that, by 2023, vaccination against COVID-19 had prevented millions of deaths worldwide, consolidating mRNA as a highly efficient vaccine platform. Such vaccines offer a number of advantages, such as no risk of integration into the host genome and rapid degradation in vivo, eliminating concerns related to antigen persistence (Chaudhary, Weissman & Whitehead, 2021). In addition, recent technical advances have made it possible to improve its intracellular stability and increase the capacity for antigen expression, resulting in more potent and long-lasting immune responses (Yılmaz *et al.*, 2021). At the same time, the capacity for large-scale production at a reduced cost represents a significant advantage for the global distribution of these immunizers, facilitating their implementation in low- and middle-income countries.

In addition to their immediate impact on the COVID-19 pandemic, mRNA vaccines have opened up new perspectives for combating various infectious diseases and even for cancer immunotherapy. Ongoing clinical trials are investigating their efficacy against HIV, influenza and malaria, reinforcing the versatility of this technology (Kutikuppala *et al.,* 2024). In addition, advances in the formulation of lipid nanoparticles (LNPs) have made it possible to improve the thermal stability of these vaccines, facilitating their global distribution and expanding their potential for use in different epidemiological contexts (Wang *et al.*, 2023). In parallel, new approaches are being studied to optimize the administration of these vaccines, including intranasal and oral formulations, which could improve vaccine adherence and facilitate their large-scale implementation (Fu *et al.*, 2024).

The safety of mRNA vaccines has been widely studied, and the available data indicate an excellent risk-benefit profile. However, rare adverse events, such as myocarditis in young populations, highlight the importance of continuous monitoring and adapting vaccine regimens as new epidemiological data emerge (Chaudhary, Weissman & Whitehead, 2021). The implementation of global pharmacovigilance systems has proven essential for the early detection of side effects and the optimization of immunization recommendations (Xu *et al.*, 2020). Despite scientific advances, ethical and logistical issues still need to be addressed, especially with regard to inequality in the global distribution of these vaccines. Low-income countries still face difficulties in

ensuring equitable access to this technology, making it essential for initiatives such as the WHO-led *COVAX Facility* to mitigate disparities and make large-scale immunization feasible (Aljabali *et al.*, 2023).

However, this technology still faces challenges, including the need to improve molecular stability, optimize formulations to maximize immune response and adapt production processes to ensure scalability and accessibility (Xu *et al.*, 2020). Although the first clinical trials have demonstrated safety and efficacy, issues such as the durability of the immune response and the applicability of these vaccines in different populations still require in-depth investigation (Aljabali *et al.*, 2023).

Given this scenario, understanding the impact and limitations of mRNA vaccines is essential to maximizing their potential in global immunization and in tackling emerging infectious diseases. This study aims to critically review the scientific advances achieved to date, addressing the efficacy, safety and technological challenges of mRNA vaccines, as well as their future prospects in preventive and therapeutic medicine. It also seeks to consolidate the available evidence on the viability of this technology for applications beyond infectious diseases, such as cancer treatment, assessing the regulatory and logistical challenges that influence its implementation.

METHODOLOGY

A literature review developed according to the criteria of the PVO strategy, which stands for: population or research problem, variables and outcome. This strategy was used to develop the research question "What is the potential of mRNA vaccines in the development of effective and safe immunizations against infectious diseases?". The searches were carried out using the PubMed - MEDLINE (Medical Literature Analysis and Retrieval System Online) databases. The search terms were used in combination with the Boolean term "AND", using the following search strategy: ("mRNA vaccines") AND ("infectious diseases") AND ("vaccine development"). From this search, 72 articles were found, which were then submitted to the selection criteria. Articles in English, published between 2020 and 2025 and addressing the proposed themes were included. Review, meta-analysis, observational and experimental studies were considered. The exclusion criteria were: duplicate articles, articles available in abstract form, articles that did not directly address the proposal studied and articles that did not meet the other inclusion criteria. After applying the inclusion and exclusion criteria, 27 articles were selected from the PubMed database to make up the collection of this study.

DISCUSSION

mRNA vaccines represent one of the most disruptive advances in biotechnology applied to immunization, setting a milestone in preventive and therapeutic medicine. The success of this technology in the COVID-19 pandemic has consolidated it as one of the most promising approaches to controlling infectious diseases, as well as opening up prospects for future applications in oncology, autoimmune diseases and emerging infections. This breakthrough resulted from the convergence of decades of research in genetic engineering, immunology and nanotechnology, culminating in the formulation of highly effective and rapid-response immunizers in a context of global health crisis (Pilkington *et al.,* 2021; Zhang C *et al.*, 2024).

The mechanism of action of mRNA vaccines is based on their ability to temporarily encode viral proteins, promoting a robust and specific immune response. The introduction of chemical modifications to nucleotides, such as pseudouridine, has made it possible to optimize the stability of RNA, reducing its innate immunogenicity and prolonging its intracellular half-life, which favors its efficient translation in the cell cytoplasm (Mengyun *et al.*, 2022; Brown *et al.*, 2023). In addition, the

encapsulation of these molecules in lipid nanoparticles (LNPs) not only protects the genetic material from enzymatic degradation, but also facilitates their internalization by antigen-presenting cells, enhancing the activation of the innate and adaptive immune system (Zhou *et al*., 2023; Machado *et al.*, 2024). This innovative technology has made it possible to create vaccines with high efficacy and accelerated production, minimizing the challenges associated with formulating new immunizers against emerging pathogens (Le et al., 2022).

In addition to innovations in the formulation of mRNA vaccines, technological advances have also been aimed at optimizing the production of these immunizers, ensuring greater efficiency and quality in the manufacturing process. Recently, the development of a method based on anion-exchange high-performance liquid chromatography (AEX-HPLC) has shown significant potential for monitoring the in vitro transcription (IVT) reactions used in mRNA synthesis. This method enables the separation and precise quantification of nucleoside triphosphates (NTPs) consumed during the reaction, allowing fine adjustments to be made to the production process to maximize mRNA yield. In addition, AEX-HPLC has been used to evaluate the efficiency of purification processes, ensuring that contaminants are removed and that a final product with high purity is obtained. The application of this protocol to monitor the production of SARS-CoV-2 spike protein mRNA has shown its usefulness in optimizing the manufacture of immunizers, contributing to the scalability and standardization of mRNA vaccine technology (Welbourne et al., 2024).

The clinical impact of mRNA vaccines has been widely documented through rigorous clinical trials, which have shown their superior efficacy in preventing symptomatic SARS--CoV-2 infection. The immunizers BNT162b2 (Pfizer-BioNTech) and mRNA-1273 (Moderna) demonstrated efficacy rates of over 90%, an unprecedented feat in the history of modern immunization (Gu *et al*., 2022; Li *et al.*, 2023). Subsequent studies have confirmed that these vaccines not only provide robust protection against severe outcomes, significantly reducing hospitalizations and deaths, but are also capable of stimulating long-term immunological memory, providing a sustained response even in the face of circulating viral variants (Fang E *et al.*, 2022). This aspect is fundamental for the epidemiological control of emerging diseases, allowing vaccine formulations to be adapted without the need for complete reconstruction of the immunizer.

In addition to SARS-CoV-2, mRNA technology has been explored for vaccines against highly mutable pathogens such as influenza, Zika and HIV. Clinical trials of the experimental mRNA-1893 vaccine, developed by Moderna against the Zika virus, demonstrated high immunogenicity, with protection sustained for up to 13 months in primates (Zhou *et al*., 2023). Similarly, studies conducted by Litvinova et al. (2023) indicate that vaccines based on mRNA encapsulated in polyamidoamine dendrimers (PAMAM) can significantly enhance the immune response against complex pathogens, including Ebola and H1N1. These findings reinforce the adaptability of the mRNA platform and its potential for the development of broad-coverage vaccines against emerging infectious diseases.

The ability to customize and adapt mRNA vaccines gives them a crucial role in responding to seasonal epidemics and future pandemics. Currently, mRNA vaccines for seasonal influenza are in phase 3 clinical trials, including formulations combined with antigens for SARS-CoV-2 and respiratory syncytial virus (RSV). If approved, these trivalent vaccines could reduce the need for multiple annual immunizations, optimizing population adherence and ensuring broad protection against circulating

respiratory viruses (Lokras *et al.,* 2024; Taaffe *et al.,* 2024). In addition, the possibility of developing personalized cancer vaccines, based on the coding of tumor neoantigens, opens up a new frontier for cancer immunotherapy, allowing highly specific and individualized treatments for different types of neoplasms (Kutikuppala *et al.*, 2024; Mir *et al.,* 2024).

However, technical and logistical challenges still need to be overcome to make mRNA vaccines widely applicable. The stability of messenger RNA remains a limiting factor, requiring storage at ultra-low temperatures to preserve its structural integrity. Innovative strategies, such as the formulation of freeze-dried mRNA and the development of circular mRNA, have been explored to minimize this limitation, since circular RNA is more resistant to enzymatic degradation and can confer longer-lasting immunogenicity (Deviatkin *et al.,* 2023; Borrajo *et al.,* 2024). In addition, the continued development of lipid nanoparticles and new delivery systems could improve the bioavailability of mRNA and reduce adverse reactions such as local inflammation and myocarditis, side effects which, although rare, have been reported mainly in young men following the administration of mRNA vaccines (Al Fayez *et al.,* 2023; Parvin, Joo, Mandal, 2024).

Vaccine hesitancy and socio-cultural barriers also pose significant challenges to the successful implementation of this technology. Misinformation and misperceptions about the risks of mRNA vaccines directly impact their acceptance by the population, requiring awareness campaigns based on scientific evidence to mitigate vaccine hesitancy and strengthen confidence in the immunization process (Mir *et al.,* 2024). In addition, inequalities in access to immunizations in low- and middle-income countries remain a critical obstacle, requiring public policies that ensure equitable distribution and adequate infrastructure for large-scale vaccination campaigns (Zhang C *et al.,* 2024).

The future prospects for mRNA vaccines are highly promising, driven by the continuous evolution of genetic engineering and applied biotechnology. The development of self-amplifying mRNA platforms could reduce the need for multiple doses, optimizing the immune response and making vaccine production more efficient and affordable. In addition, passive immunization via messenger RNA encoding monoclonal antibodies is emerging as a revolutionary approach to preventing chronic diseases and persistent infections (Deviatkin *et al.*, 2023; Lokras *et al.,* 2024). Continued research in this field could further expand the applications of mRNA vaccines, consolidating them as a central pillar of translational medicine and modern immunology.

FINAL CONSIDERATIONS

mRNA vaccines represent a milestone in immunization against infectious diseases, demonstrating high efficacy and flexibility in dealing with emerging pathogens and new viral variants. Advances such as self-amplifying mRNA and structural optimizations improve its stability, reducing the need for repeated doses. In addition to infectious diseases, this technology opens up prospects in cancer immunotherapy and the treatment of chronic diseases. However, challenges such as thermal stability, cell targeting and adverse immunological reactions still require improvement. The integration of nanotechnology and bioinformatics could further expand its applicability. The success of the platform, however, will depend on continued investment in research, technological innovation and effective scientific communication. Thus, mRNA vaccines are consolidating their position as an essential tool in global immunization and the advancement of precision medicine.

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