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The future of vaccines: Advancements in mRNA technology beyond COVID-19

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Abstract

Background: Since their emergency authorization in 2020, mRNA vaccines transformed global vaccinology demonstrating remarkable speed, flexibility, and efficacy, particularly in the COVID-19 response. These successes have catalyzed exploration of broader applications of mRNA platforms beyond SARS-CoV-2.

mRNA vaccine technology matured rapidly during the COVID-19 pandemic, demonstrating speed, scalability, and robust protective efficacy. Beyond SARS-CoV-2, the platform is expanding into prophylactic vaccines for respiratory and endemic pathogens, difficult viral targets (e.g., CMV, HIV), complex bacterial threats (e.g., *M. tuberculosis*), parasitic diseases (e.g., malaria), and therapeutic applications in oncology, allergy, and autoimmunity. Key advances include self-amplifying and trans-amplifying mRNA, circular RNA, improved untranslated regions (UTRs), next-generation lipid nanoparticles and polymeric carriers, thermo stabilization, alternative delivery routes (Intranasal, oral, micro needle patches), and AI-assisted antigen design. This narrative review synthesizes platform innovations, immunological mechanisms, manufacturing and regulatory considerations, safety and reactogenicity, equity and access, and outlines a roadmap for the next decade of mRNA vaccinology.

Keywords: mRNA vaccines, self-amplifying mRNA, Circular RNA, lipid nanoparticles, thermostability, intranasal vaccines, cancer neoantigen vaccines, global health, regulatory science, pharmacovigilance

Introduction

The rapid deployment of mRNA vaccines against SARS-CoV-2 marked a watershed in vaccinology. The modularity of mRNA where informational content (coding sequence) is decoupled from a largely fixed delivery formulation allows rapid re-targeting to new pathogens or antigens without re-engineering the core manufacturing process. As clinical and real-world evidence accumulated for safety and efficacy against COVID-19, interest has widened to persistent high-burden diseases and therapeutic indications. Here we provide a forward-looking synthesis, with emphasis on scientific and engineering advances that expand indications, improve durability, enable needle-free delivery, and reduce cost and cold-chain constraints.

Scope

This article reviews the evolution and future potential of mRNA technologies, focusing on:-

- Next-generation mRNA platforms like self-amplifying RNA (saRNA), which enhance potency and durability at lower doses.
- Innovative delivery systems, including ionizable lipids, dendrimer-based carriers, exosomes, and methods beyond lipid nanoparticles, aimed at improving targeting, safety, and thermostability.
- Applications beyond COVID-19, spanning personalized cancer vaccines (neoantigen-based and targeting tumor-associated antigens), diverse infectious diseases such as influenza, RSV, CMV, HIV, Zika, and bacterial pathogens like plague, as well as genetic and rare diseases.
- Challenges such as cold-chain dependence, global manufacturing disparities especially in low- and middle-income countries, and regulatory and logistical barriers.
- Future outlook, including advances in mRNA stability, antigen design, artificial intelligence integration for precision vaccine development, and global equity through collaborative manufacturing initiatives.

Conclusions

mRNA technology is poised to revolutionize vaccine science extending far beyond COVID-19 into oncology, rare diseases, and beyond. Realizing this promise requires continued innovation in platform stability, delivery, manufacturing scale-up, and inclusive global access.

Conflict of Interest

Not available

Financial Support

Not available

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