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Review Article

mRNA Technology and Its Future in Vaccine Development: Recent Advances, Pharmaceutical Applications and Challenges

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ABSTRACT

Messenger RNA (mRNA) technology has emerged as a revolutionary approach in modern vaccine development. Unlike conventional vaccines, which use weakened or inactivated pathogens or purified antigens, mRNA vaccines introduce genetic instructions into human cells to produce a specific antigen that stimulates an immune response. The success of mRNA-based COVID-19 vaccines has accelerated research into their applications against infectious diseases, cancer and other medical conditions. Recent developments in lipid nanoparticle (LNP) delivery systems, self-amplifying mRNA (saRNA), circular RNA (circRNA) and molecular engineering have improved the potential of this technology. In India, the development of GEMCOVAC-19 has demonstrated the potential of mRNA-based vaccine research using indigenous technology. New research is also investigating improved storage stability, targeted delivery and personalized cancer vaccines. This review discusses the fundamental principles of mRNA technology, its mechanism of action, formulation, pharmaceutical applications, recent advancements, advantages, limitations and future prospects in vaccine development.

INTRODUCTION

Vaccines are among the most effective tools in preventive healthcare. Traditional vaccine technologies include live attenuated vaccines, inactivated vaccines, subunit vaccines and toxoid vaccines. Although these technologies have contributed significantly to disease prevention, they may require lengthy development procedures and complex manufacturing processes.

Messenger RNA technology represents a new approach to vaccine development. mRNA is a genetic molecule that carries instructions from DNA to cellular ribosomes, where proteins are synthesized.

In mRNA vaccination, a synthetic mRNA sequence encoding a selected antigen is delivered into the body's cells. The cells use this genetic information to produce the antigen, which is subsequently recognized by the

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immune system. This stimulates antibody production and cellular immune responses.

The COVID-19 pandemic accelerated the development and clinical application of this technology. The Pfizer-BioNTech and Moderna COVID-19 vaccines demonstrated that mRNA platforms could be developed rapidly and manufactured on a large scale.

Today, researchers are exploring mRNA technology for influenza, respiratory syncytial virus (RSV), HIV, malaria, tuberculosis and cancer immunotherapy.

2. History and Development of mRNA Technology

The scientific foundation of mRNA technology was established through research into messenger RNA and protein synthesis.

Important milestones include:

- 1961: Messenger RNA was identified as an intermediate molecule involved in protein synthesis.
- 1990: Researchers demonstrated protein production following the injection of mRNA into animals.
- 2005: Nucleoside modification research demonstrated ways to reduce unwanted inflammatory responses and improve protein expression.
- 2010 onwards: Lipid nanoparticle delivery systems advanced the development of mRNA therapeutics.
- 2020: Pfizer-BioNTech and Moderna introduced mRNA-based COVID-19 vaccines.
- 2023: The Nobel Prize in Physiology or Medicine was awarded to Katalin Karikó and Drew Weissman for discoveries that enabled effective mRNA vaccines.
- 2023: India's GEMCOVAC-19 became an important example of indigenous mRNA vaccine development.
- 2024 onwards: Research expanded into influenza, RSV, combination vaccines and personalized cancer vaccines.
- 2026: Research increasingly focuses on thermostable formulations, self-amplifying RNA, circular RNA and personalized cancer vaccine manufacturing.

Principle of mRNA Vaccine Technology

The basic principle of mRNA vaccination is the delivery of genetic instructions into host cells to produce a specific antigen.

The antigen produced inside the cells activates the immune system and helps the body develop protection against the targeted disease.

The mRNA itself does not contain the complete infectious organism and cannot cause the targeted infection through the mechanism of antigen expression.

Mechanism of Action of mRNA Vaccines

The mechanism of action involves several important steps.

Step 1: Vaccine Administration

The mRNA vaccine is administered, usually through intramuscular injection. The mRNA is protected from degradation by a lipid nanoparticle delivery system.

Step 2: Cellular Uptake

The lipid nanoparticles are taken up by cells through endocytosis.

Step 3: Release of mRNA

Following cellular uptake, a fraction of the mRNA escapes from the endosome into the cytoplasm.

Step 4: Protein Synthesis

The cellular ribosomes recognize the mRNA and translate its genetic instructions into the required antigenic protein.

Step 5: Antigen Presentation

The produced antigen is processed and presented through major histocompatibility complex (MHC) pathways.

Step 6: Immune System Activation

The immune system recognizes the antigen and activates:

- B lymphocytes for antibody production.
- CD4+ T lymphocytes for immune coordination.
- CD8+ T lymphocytes for cellular immune responses.

Step 7: Immunological Memory

Memory B cells and T cells may develop, helping the immune system respond more effectively to subsequent exposure to the pathogen.

5. Components of an mRNA Vaccine

An mRNA vaccine contains several essential components.

1 Messenger RNA

The mRNA contains the genetic instructions required for producing the target antigen.

2 5′ Cap

The 5′ cap protects mRNA against degradation and supports ribosome recognition and translation.

3 Untranslated Regions (UTRs)

The 5′ and 3′ untranslated regions regulate mRNA stability and translation efficiency.

4 Coding Region

This region contains the nucleotide sequence responsible for encoding the desired antigen.

5 Poly (A) Tail

The poly (A) tail helps improve mRNA stability and supports efficient translation.

6 Lipid Nanoparticles

Lipid nanoparticles protect mRNA against enzymatic degradation and facilitate its delivery into cells.

LNP formulations commonly contain:

- Ionizable lipids.
- Phospholipids.
- Cholesterol.
- Polyethylene glycol (PEG)-lipids.

Types of mRNA Vaccine Technology

1 Conventional or Non-Replicating mRNA

This type of mRNA contains instructions for producing the target antigen but does not encode an RNA replication system.

It is the platform used in widely known COVID-19 vaccines.

2 Self-Amplifying mRNA (saRNA)

Self-amplifying mRNA contains additional genetic instructions encoding replication proteins. These enable the RNA to amplify intracellularly and produce more antigen from a comparatively small initial dose.

Potential advantages include:

- Lower dose requirements.
- Improved antigen expression.
- Potential manufacturing efficiencies.

3 Circular RNA (circRNA)

Circular RNA is a closed-loop RNA molecule that lacks the conventional free ends found in linear RNA.

Its circular structure can provide increased resistance to exonuclease-mediated degradation. Researchers are investigating its potential for prolonged protein expression and improved vaccine stability.

However, circRNA vaccines remain an emerging research platform, and further clinical evaluation is required.

Pharmaceutical Applications of mRNA Technology

1 COVID-19 Vaccines

The COVID-19 pandemic demonstrated the clinical potential of mRNA vaccines.

Pfizer-BioNTech and Moderna developed mRNA vaccines targeting the SARS-CoV-2 spike protein. These vaccines helped establish mRNA technology as an important platform for infectious disease prevention.

2 Influenza Vaccines

Researchers are investigating mRNA-based influenza vaccines to improve vaccine development and allow more rapid adaptation to circulating influenza strains.

3 Respiratory Syncytial Virus (RSV)

RSV is an important cause of respiratory infections, particularly in infants, older adults and vulnerable individuals.

mRNA technology has enabled the development of RSV vaccine candidates and an approved mRNA-based RSV vaccine.

.4 Cancer Vaccines

One of the most promising applications of mRNA technology is cancer immunotherapy.

Personalized mRNA cancer vaccines are designed using genetic information obtained from an individual patient's tumour.

These vaccines encode selected tumour-associated or tumour-specific antigens called neoantigens. The objective is to stimulate immune cells to recognize and attack cancer cells.

.5 HIV and Other Infectious Diseases

Researchers are investigating mRNA vaccines against HIV, malaria, tuberculosis, Zika and rabies.

These applications remain at different stages of research and clinical development.

Recent Developments in mRNA Technology (2025–2026)

1 Development of Self-Amplifying RNA Vaccines

Self-amplifying RNA technology has emerged as a promising next-generation vaccine platform.

India's GEMCOVAC-19 is an important example of an indigenous self-amplifying mRNA COVID-19 vaccine. This demonstrates the growing role of Indian biotechnology in advanced vaccine research.

2 Improved Vaccine Storage Stability

Conventional mRNA vaccines can require controlled low-temperature storage because RNA molecules are sensitive to degradation.

Recent research is focusing on:

- Thermostable lipid nanoparticle formulations.
- Lyophilized vaccine formulations.
- Improved RNA molecular structures.
- Refrigeration-compatible formulations.

These innovations may improve vaccine distribution in countries with limited cold-chain infrastructure.

.3 Personalized mRNA Cancer Vaccines

Personalized cancer vaccines are receiving significant attention.

In November 2026, reports on the Phase III INTerpath-001 trial of intismeran autogene, developed by Moderna and Merck, highlighted promising melanoma results when used with pembrolizumab. The trial reported a 42% reduction in the risk of recurrence or death compared with the control approach.

This is an important development in the investigation of individualized cancer immunotherapy. The product remains subject to the relevant regulatory evaluation and should not be considered an approved cancer vaccine on the basis of these results alone.

4 Combination mRNA Vaccines

Researchers are investigating combination vaccines targeting multiple diseases, such as:

- COVID-19 and influenza.
- COVID-19 and RSV.
- Influenza and other respiratory pathogens.

Combination vaccines could reduce the number of separate injections required and simplify immunization schedules if their safety and efficacy are established.

5 Artificial Intelligence in mRNA Vaccine Design

Artificial intelligence and machine learning are being investigated to improve:

- Antigen selection.
- mRNA sequence optimization.
- Prediction of protein structures.
- Lipid nanoparticle formulation.
- Vaccine candidate screening.

These tools may accelerate the research and development process.

Advantages of mRNA Vaccine Technology

1. Rapid vaccine design and development.
2. Flexible platform suitable for different target diseases.
3. Does not require cultivation of the infectious pathogen for antigen production.
4. Potential for large-scale manufacturing.
5. Ability to stimulate both humoral and cellular immunity.
6. Easy modification of genetic sequences to target emerging variants.

7. Potential application in personalized cancer treatment.
8. No need for mRNA to enter the cell nucleus or integrate into genomic DNA as part of its normal mechanism of action.

Limitations and Challenges

Despite its advantages, mRNA technology has certain limitations.

1 RNA Instability

mRNA is susceptible to degradation by RNase enzymes, making formulation and storage important considerations.

2 Cold-Chain Requirements

Some mRNA vaccines require strict temperature control during transportation and storage, which can increase distribution costs.

.3 Reactogenicity

Common short-term adverse effects can include injection-site pain, fatigue, fever, headache and muscle pain.

Rare adverse events, including myocarditis and pericarditis, have been associated with certain mRNA COVID-19 vaccines and require continued monitoring.

4 Manufacturing Complexity

The production process requires specialized facilities, high-quality raw materials, stringent quality control and validated manufacturing procedures.

.5 Cost and Accessibility

Advanced manufacturing requirements and infrastructure costs can limit accessibility in low-resource settings.

6 Public Acceptance

Vaccine hesitancy, misinformation and concerns about new technologies may affect public acceptance.

Role of mRNA Technology in the Indian Pharmaceutical Industry

India has an established pharmaceutical and vaccine manufacturing sector. The development of mRNA technology provides opportunities for strengthening domestic biotechnology research.

GEMCOVAC-19, developed by Gennova Biopharmaceuticals, is an important example of indigenous self-amplifying mRNA vaccine development.

Potential opportunities for Indian pharmaceutical companies include:

- Development of indigenous mRNA vaccine platforms.
- Manufacturing of lipid nanoparticle formulations.
- Research into thermostable vaccines.
- Development of vaccines against emerging infectious diseases.
- Expansion of biotechnology research and development.
- Collaboration between pharmaceutical industries and academic institutions.

India's experience in vaccine manufacturing may support the development of advanced RNA-based pharmaceutical products.

Future Prospects of mRNA Technology

The future of mRNA technology extends beyond conventional preventive vaccination.

Promising research areas include:

A. Universal influenza vaccines: Development of vaccines targeting conserved viral regions to provide broader protection.

B. Personalized cancer vaccines: Designing individualized vaccines based on the genetic characteristics of a patient's tumour.

C. HIV vaccines: Using sequential immunization strategies to stimulate broadly neutralizing antibody responses.

D. Combination vaccines: Developing a single vaccine formulation targeting multiple infectious diseases.

E. Circular RNA vaccines: Investigating improved stability and longer antigen-expression profiles.

F. Targeted delivery systems: Developing advanced nanoparticles that deliver mRNA to specific tissues or immune cells.

G. Thermostable formulations: Improving vaccine storage and transportation without requiring extensive ultra-cold infrastructure.

H. AI-assisted vaccine development: Using computational tools to optimize antigen sequences, RNA structures and delivery systems.

CONCLUSION

mRNA technology represents a major advancement in pharmaceutical biotechnology and modern vaccine development. The success of COVID-19 vaccines has established the clinical potential of this platform and encouraged research into several infectious and non-infectious diseases.

Advancements in lipid nanoparticle delivery systems, self-amplifying RNA, circular RNA and personalized cancer vaccines are expanding the applications of this technology.

However, challenges involving stability, storage, manufacturing costs, safety monitoring and equitable accessibility must be addressed.

India has significant opportunities to contribute to this field through indigenous vaccine research, biotechnology innovation and advanced pharmaceutical manufacturing.

In conclusion, mRNA technology has the potential to transform future vaccine development by providing a flexible, adaptable and scientifically advanced platform for preventive and therapeutic medicine.

REFERENCES

1. Pardi N, Hogan MJ, Porter FW, Weissman D. mRNA vaccines — a new era in vaccinology. Nature Reviews Drug Discovery. 2018;17:261–279.
2. Karikó K, Buckstein M, Ni H, Weissman D. Suppression of RNA recognition by Toll-like receptors: The impact of nucleoside modification and the evolutionary origin of RNA. Immunity. 2005;23 (2):165–175.
3. Sahin U, Karikó K, Türeci Ö. mRNA-based therapeutics — developing a new class of drugs. Nature Reviews Drug Discovery. 2014;13:759–780.
4. Pardi N, Hogan MJ, Weissman D. Recent advances in mRNA vaccine technology. Current Opinion in Immunology. 2020;65:14–20.
5. Hou X, Zaks T, Langer R, Dong Y. Lipid nanoparticles for mRNA delivery. Nature Reviews Materials. 2021;6:1078–1094.
6. Eshaghi B, Langer R, Jaklenec A. Expanding global access to mRNA vaccines. Nature Reviews Bioengineering. 2026;4:614–635.
7. Wang H, Zhuo R, Wu J, et al. Bioengineering strategies for improving the immunogenicity of mRNA vaccines. Signal Transduction and Targeted Therapy. 2026;11:430.
8. World Health Organization. mRNA vaccines: scientific and public health developments. https://www.who.int/
9. Centers for Disease Control and Prevention. Understanding mRNA COVID-19 vaccines. https://www.cdc.gov/covid/
10. Department of Biotechnology, Government of India. Information on indigenous vaccine development. https://dbtindia.gov.in/
11. Gennova Biopharmaceuticals. GEMCOVAC-19 vaccine development information. https://www.gennova.bio/
12. National Center for Biotechnology Information. Literature and research on mRNA vaccines. https://pubmed.ncbi.nlm.nih.gov/

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