Volume 1, Issue 2, July-September 2026

e-ISSN: AWAITING

INTERNATIONAL JOURNAL OF
Medical and Healthcare Sciences (IJMedHS)

OPEN ACCESS

Journal homepage: https://jmedhsscience.com/

Advancing Cancer Immunotherapy: The Role of mRNA Vaccine Platforms

Rutuja Chandu Mahure[1*], Varun Rajendra Khorate[2]

[1,2]Bharati Vidyapeeth College of Pharmacy, Kolhapur, Maharashtra, 416 013, India
[1]rutumahure@gmail.com, [2]varunkhorate9944@gmail.com
[1]Orcid ID: 0009-0001-3138-2529, **[2]Orcid ID:** 0009-0007-1752-0108

Corresponding Auther:- rutumahure@gmail.com

Article Info

Received: 28 July 2026
Accepted: 30 August 2026
Published: 02 September 2026

*Mahure R. M.,
Advancing Cancer Immunotherapy: The Role of mRNA Vaccine Platforms,
International Journal of Medical & Healthcare Sciences [IJMedHS], 1(2), 01-08
DOI:

ABSTRACT

Cancer remains a leading cause of morbidity and mortality worldwide, necessitating the development of innovative and targeted therapeutic strategies beyond conventional treatments such as chemotherapy and radiotherapy. In recent years, cancer immunotherapy has emerged as a transformative approach that harnesses the body's immune system to recognize and eliminate malignant cells. Among the various immunotherapeutic modalities, messenger RNA (mRNA)-based vaccines have gained significant attention due to their safety, flexibility, and rapid development capabilities.

mRNA cancer vaccines function by delivering synthetic mRNA encoding tumor-associated or tumor-specific antigens into host cells, particularly antigen-presenting cells, leading to in situ production of antigenic proteins. These antigens are subsequently presented via major histocompatibility complex pathways, activating both cellular ($CD8^+$ cytotoxic T cells) and humoral immune responses. The ability to induce robust and specific anti-tumor immunity, coupled with a favorable safety profile—owing to the non-infectious and non-integrating nature of mRNA—positions this platform as a promising tool in oncology.

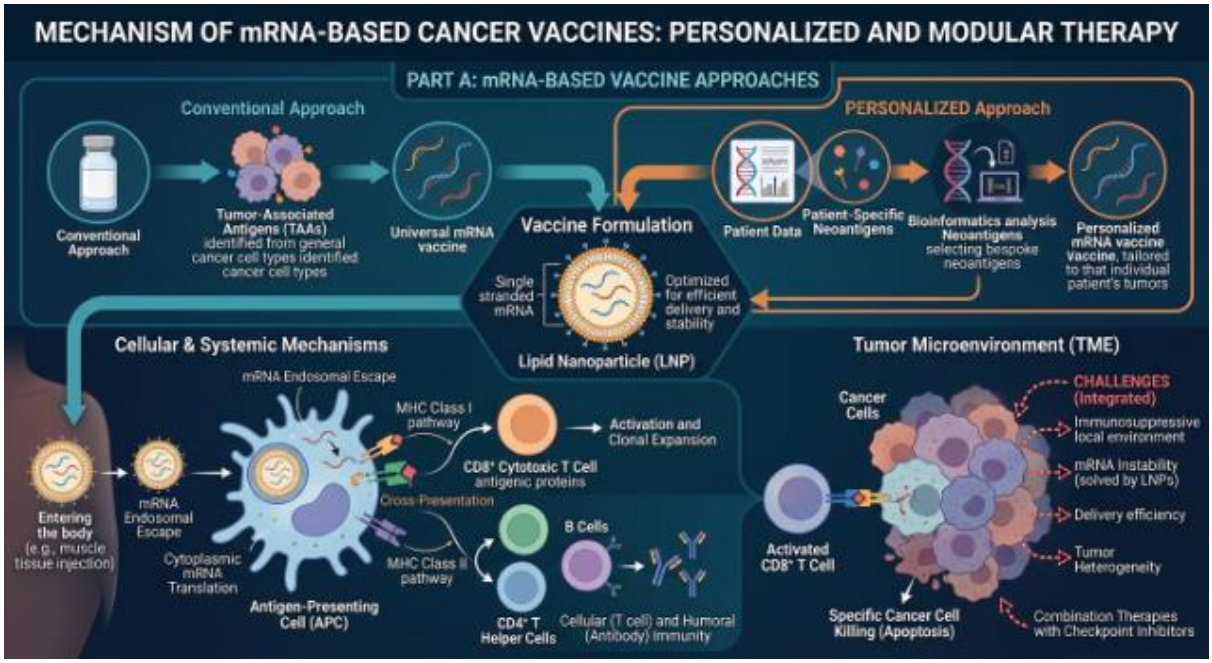
Advancements in mRNA design, including structural optimization and incorporation of modified nucleosides, along with the development of efficient delivery systems such as lipid nanoparticles, have significantly enhanced vaccine stability and efficacy. Furthermore, the emergence of personalized mRNA vaccines targeting patient-specific neoantigens represents a major breakthrough in precision medicine.

Despite these advantages, challenges such as mRNA instability, delivery efficiency, tumor heterogeneity, and immunosuppressive tumor microenvironments remain. Ongoing clinical trials and research efforts continue to address these limitations and explore combination therapies with immune checkpoint inhibitors and other modalities.

In conclusion, mRNA-based cancer vaccines represent a novel and rapidly evolving approach in cancer immunotherapy, with the potential to revolutionize cancer treatment through personalized, targeted, and effective therapeutic strategies.

Keywords: mRNA vaccines; Cancer immunotherapy; Tumor-associated antigens (TAAs); Neoantigens; Lipid nanoparticles (LNPs); Antigen-presenting cells (APCs); $CD8^+$ T cells; Personalized cancer vaccines; Precision oncology

Graphical Abstract



1. Introduction

Cancer continues to be one of the leading causes of mortality worldwide, representing a major burden on public health systems and economies. According to global health statistics, millions of new cancer cases are diagnosed each year, with a significant proportion resulting in death despite advancements in diagnostic and therapeutic technologies. Conventional cancer treatment modalities such as surgery, chemotherapy, and radiotherapy have undoubtedly improved survival rates; however, they are often associated with significant limitations, including lack of specificity, systemic toxicity, development of resistance, and recurrence of disease. These challenges have necessitated the development of innovative therapeutic strategies that are more targeted, effective, and safer.

In this context, cancer immunotherapy has emerged as a revolutionary approach that leverages the body's own immune system to combat cancer. Unlike traditional treatments that directly target tumor cells, immunotherapy enhances the immune system's ability to recognize and destroy malignant cells. The immune system is naturally equipped with mechanisms to identify abnormal cells through antigen recognition. Cancer cells often express abnormal proteins known as tumor-associated antigens (TAAs) or tumor-specific antigens (TSAs), including neoantigens that arise due to genetic mutations. These antigens serve as potential targets for immune-mediated destruction.

However, cancer cells are highly adaptive and can evade immune surveillance through various mechanisms. These include downregulation of antigen presentation pathways, secretion of immunosuppressive cytokines, recruitment of regulatory T cells, and expression of immune checkpoint molecules such as PD-1 and CTLA-4. As a result, the immune system fails to effectively eliminate tumor cells, allowing cancer progression. This has led to the development of immunotherapeutic strategies such as immune checkpoint inhibitors, monoclonal antibodies, adoptive T-cell therapy, and cancer vaccines.

Among these approaches, cancer vaccines have gained significant attention due to their ability to induce a specific and durable immune response against tumor cells. Unlike preventive vaccines used against infectious diseases, therapeutic cancer vaccines aim to treat existing cancers by stimulating the immune system to target tumor-specific antigens. Within this category, mRNA-based cancer vaccines have emerged as a highly promising and innovative platform.

The concept of mRNA vaccines is based on the delivery of synthetic messenger RNA encoding specific antigens into host cells. Once inside the cell, the mRNA is translated into proteins that mimic tumor antigens, thereby triggering an immune response. This technology gained widespread recognition during the COVID-19 pandemic, where mRNA vaccines demonstrated rapid development, high efficacy, and excellent safety profiles. These advantages have accelerated the exploration of mRNA vaccines in oncology.

mRNA cancer vaccines offer several unique advantages over traditional vaccine platforms. They are non-infectious, eliminating the risk associated

with live or attenuated pathogens. Additionally, mRNA does not integrate into the host genome, ensuring a favorable safety profile. One of the most significant advantages is the speed of development, as mRNA vaccines can be rapidly designed and synthesized based on the genetic sequence of tumor antigens. This makes them highly adaptable for personalized medicine, where vaccines can be tailored to individual patients based on their tumor mutations.

Another critical advancement in mRNA vaccine technology is the development of efficient delivery systems, particularly lipid nanoparticles (LNPs). These nanocarriers protect mRNA from enzymatic degradation and facilitate its delivery into cells, enhancing stability and translation efficiency. Furthermore, modifications in mRNA structure, such as optimized codons, modified nucleosides, and improved untranslated regions (UTRs), have significantly improved the immunogenicity and stability of mRNA vaccines.

Despite these promising features, challenges remain in the clinical translation of mRNA cancer vaccines. Issues such as mRNA instability, need for ultra-cold storage, delivery efficiency, and tumor-induced immunosuppression must be addressed. Nevertheless, ongoing research and clinical trials continue to demonstrate encouraging results, particularly in cancers such as melanoma, lung cancer, and pancreatic cancer.

The integration of mRNA vaccines with other immunotherapeutic approaches, such as immune checkpoint inhibitors, represents a promising strategy to enhance therapeutic efficacy. Combination therapies can overcome immune resistance mechanisms and improve patient outcomes. Moreover, advances in genomics and bioinformatics have enabled the identification of patient-specific neoantigens, paving the way for personalized mRNA cancer vaccines.

In conclusion, mRNA vaccine platforms represent a transformative advancement in cancer immunotherapy. Their ability to induce targeted immune responses, combined with their safety and flexibility, positions them as a key component of future cancer treatment strategies. As research continues to evolve, mRNA vaccines have the potential to revolutionize oncology and significantly improve patient survival and quality of life.

2. Mechanism of Action and Immunological Basis

The mechanism of action of mRNA cancer vaccines is rooted in the fundamental principles of molecular biology and immunology. These vaccines are designed to mimic natural infection processes without introducing pathogenic material, thereby activating the immune system in a controlled and targeted manner. The process begins with the administration of synthetic mRNA encoding tumor-associated or tumor-specific antigens.

Once administered, the mRNA is delivered into host cells, primarily antigen-presenting cells (APCs) such as dendritic cells. These cells play a crucial role in initiating immune responses. Delivery systems, particularly lipid nanoparticles, facilitate the uptake of mRNA into cells via endocytosis. After internalization, the mRNA escapes from endosomes into the cytoplasm, where it is translated into antigenic proteins by ribosomes.

These newly synthesized proteins undergo intracellular processing and are degraded into peptide fragments. These peptides are then loaded onto major histocompatibility complex (MHC) molecules. MHC class I molecules present antigens to $CD8^+$ cytotoxic T lymphocytes (CTLs), while MHC class II molecules present antigens to $CD4^+$ helper T cells.

Activation of $CD8^+$ T cells is a critical step in anti-tumor immunity. These cells recognize and bind to antigen-MHC complexes on tumor cells and induce apoptosis through the release of cytotoxic molecules such as perforin and granzymes. $CD4^+$ helper T cells, on the other hand, enhance immune responses by secreting cytokines that support the activation and proliferation of CTLs and B cells.

In addition to cellular immunity, mRNA vaccines also stimulate humoral immune responses. B cells recognize antigenic proteins and differentiate into plasma cells that produce antibodies. These antibodies can bind to tumor antigens, facilitating their destruction through mechanisms such as antibody-dependent cellular cytotoxicity (ADCC).

Another important aspect of mRNA vaccine action is the generation of immunological memory. Memory T and B cells are formed during the immune response, providing long-term protection against tumor recurrence. This is particularly important in preventing relapse, which is a common challenge in cancer treatment.

The immunogenicity of mRNA vaccines is influenced by several factors, including mRNA structure, delivery system, and innate immune activation. mRNA molecules can activate innate immune receptors such as toll-like receptors (TLRs), leading to the production of type I interferons and other cytokines. While this enhances immune responses, excessive activation may reduce mRNA translation efficiency. Therefore, careful optimization of mRNA design is necessary.

Modified nucleosides, such as pseudouridine, are often incorporated into mRNA to reduce innate immune activation and improve stability. Similarly, optimization of untranslated regions (UTRs) and

codon usage enhances translation efficiency and protein expression.

The delivery system plays a crucial role in determining the success of mRNA vaccines. Lipid nanoparticles are currently the most widely used carriers due to their ability to protect mRNA from degradation, facilitate cellular uptake, and promote endosomal escape. Advances in nanotechnology have led to the development of more efficient and targeted delivery systems.

Tumor microenvironment (TME) also plays a significant role in determining the efficacy of mRNA vaccines. The TME often contains immunosuppressive cells such as regulatory T cells and myeloid-derived suppressor cells, which inhibit immune responses. Overcoming these barriers is essential for achieving effective anti-tumor immunity.

Combination therapies involving mRNA vaccines and immune checkpoint inhibitors have shown promising results in overcoming immune suppression. These inhibitors block proteins such as PD-1 and CTLA-4, restoring T-cell activity and enhancing the efficacy of vaccines.

In summary, the mechanism of action of mRNA cancer vaccines involves a complex interplay of molecular and immunological processes. By inducing both cellular and humoral immune responses and generating immunological memory, these vaccines offer a powerful strategy for cancer treatment.

3. Types, Components, and Formulation Strategies

mRNA cancer vaccines can be broadly classified into different types based on their structure and functional characteristics. The two primary categories are non-replicating mRNA vaccines and self-amplifying mRNA vaccines.

Non-replicating mRNA vaccines are the simplest form and consist of mRNA encoding the desired antigen. These vaccines rely on cellular machinery for translation and protein production. They are relatively easy to design and manufacture, making them suitable for rapid development and personalized therapies.

Self-amplifying mRNA vaccines, on the other hand, contain additional genetic elements derived from viral genomes that enable intracellular replication of mRNA. This results in higher antigen expression and enhanced immune responses. However, these vaccines are more complex and may pose additional safety considerations.

The design of mRNA vaccines involves several critical components. The mRNA sequence encodes the target antigen and is optimized for efficient translation. The 5′ cap structure is essential for mRNA stability and initiation of translation. Untranslated regions (UTRs) play regulatory roles and influence mRNA stability and translation efficiency. The poly(A) tail further enhances stability and prevents degradation.

Delivery systems are a crucial component of mRNA vaccine formulation. Lipid nanoparticles are the most widely used carriers due to their ability to encapsulate mRNA, protect it from degradation, and facilitate cellular uptake. These nanoparticles are composed of ionizable lipids, cholesterol, phospholipids, and polyethylene glycol (PEG)-lipids.

Formulation strategies focus on optimizing stability, delivery efficiency, and immunogenicity. Advances in nanotechnology have enabled the development of targeted delivery systems that can selectively deliver mRNA to specific cells or tissues. This improves therapeutic efficacy and reduces side effects.

Lyophilization and other stabilization techniques are being explored to overcome storage challenges associated with mRNA vaccines. Ultra-cold storage requirements remain a significant limitation, particularly in resource-limited settings.

4. Clinical Applications, Challenges, and Future Prospects

mRNA cancer vaccines are currently being evaluated in numerous clinical trials for various types of cancer, including melanoma, lung cancer, breast cancer, prostate cancer, and pancreatic cancer. Early-phase clinical studies have demonstrated encouraging results, particularly in melanoma, where personalized mRNA vaccines have shown improved survival rates.

Despite these promising outcomes, several challenges must be addressed. mRNA instability, delivery efficiency, and high production costs remain significant barriers. Additionally, tumor heterogeneity and immune evasion mechanisms complicate treatment outcomes.

Personalized mRNA vaccines represent a major advancement in oncology. By sequencing tumor DNA and identifying neoantigens, customized vaccines can be developed for individual patients. This approach enhances specificity and reduces off-target effects.

The future of mRNA cancer vaccines lies in combination therapies, improved delivery systems, and advancements in genomics and bioinformatics. Integration with immune checkpoint inhibitors and other immunotherapies is expected to significantly enhance efficacy.

In conclusion, mRNA vaccine platforms have the potential to revolutionize cancer treatment. Continued research and innovation will be essential to overcome existing challenges and fully realize their therapeutic potential.

5. Advantages of mRNA Cancer Vaccines

mRNA cancer vaccines have emerged as a transformative innovation in oncology due to their multiple scientific, clinical, and manufacturing advantages over conventional therapeutic approaches. These advantages position mRNA technology as a cornerstone in the future of personalized and precision medicine.

One of the most significant advantages of mRNA cancer vaccines is their high specificity. Unlike chemotherapy and radiotherapy, which often damage both cancerous and healthy cells, mRNA vaccines are designed to target tumor-specific antigens or neoantigens. This targeted approach minimizes off-target effects and reduces systemic toxicity. The ability to encode multiple antigens within a single mRNA construct further enhances the breadth of immune response, allowing simultaneous targeting of heterogeneous tumor populations.

Another major advantage is the rapid development and manufacturing capability of mRNA vaccines. Traditional vaccine platforms often require time-consuming processes such as cell culture, protein purification, or viral vector production. In contrast, mRNA vaccines can be synthesized quickly using in vitro transcription once the genetic sequence of the target antigen is known. This rapid turnaround is particularly valuable in cancer therapy, where timely intervention is critical.

mRNA vaccines also offer an excellent safety profile. Since mRNA is a non-infectious molecule and does not integrate into the host genome, the risk of insertional mutagenesis is virtually eliminated. Additionally, mRNA is naturally degraded by cellular processes after translation, reducing long-term safety concerns. This transient expression ensures that antigen production is controlled and does not persist unnecessarily in the body.

The flexibility and adaptability of mRNA platforms are another key advantage. The same manufacturing process can be used to produce different vaccines by simply altering the encoded mRNA sequence. This makes mRNA technology highly versatile and suitable for a wide range of cancer types. Furthermore, it enables the development of personalized cancer vaccines, where individual tumor mutations are targeted.

Another critical benefit is the ability of mRNA vaccines to induce both cellular and humoral immune responses. Activation of $CD8^+$ cytotoxic T cells leads to direct killing of tumor cells, while $CD4^+$ helper T cells and B cells contribute to immune regulation and antibody production. This dual immune activation enhances overall therapeutic efficacy.

The incorporation of lipid nanoparticle (LNP) delivery systems has further strengthened the potential of mRNA vaccines. These nanoparticles protect mRNA from enzymatic degradation and facilitate efficient cellular uptake. Additionally, LNPs can act as adjuvants, enhancing immune stimulation without the need for additional immunostimulatory agents.

mRNA vaccines also support scalability and cost-effectiveness in the long term. Although initial production costs may be high, the standardized manufacturing process and absence of complex biological systems reduce variability and enable large-scale production.

Furthermore, mRNA vaccines are highly suitable for combination therapies. They can be effectively combined with immune checkpoint inhibitors, chemotherapy, radiotherapy, or targeted therapies to enhance therapeutic outcomes. Such combinations can overcome tumor immune evasion and improve response rates.

Another emerging advantage is the ability to incorporate self-amplifying mRNA, which increases antigen expression within cells, thereby reducing the required dose and enhancing immune responses. This innovation has the potential to improve both efficacy and cost-efficiency.

In summary, the advantages of mRNA cancer vaccines—including specificity, safety, rapid development, flexibility, and strong immune activation—make them a highly promising therapeutic platform. These features collectively support their growing role in modern oncology.

6. Limitations and Challenges

Despite their remarkable potential, mRNA cancer vaccines face several scientific, technical, and clinical challenges that must be addressed to achieve widespread clinical success.

One of the primary challenges is the intrinsic instability of mRNA molecules. mRNA is highly susceptible to degradation by ribonucleases (RNases), which are abundant in biological environments. This instability necessitates the use of protective delivery systems such as lipid nanoparticles. However, even with these systems, maintaining stability during storage and transportation remains a significant hurdle.

Closely related to this issue is the requirement for ultra-cold storage conditions. Many mRNA vaccines require storage at temperatures as low as −70°C to maintain stability. This presents logistical challenges, particularly in low- and middle-income countries where cold-chain infrastructure may be limited. Efforts are ongoing to develop thermostable formulations that can be stored at higher temperatures.

Another major challenge is efficient delivery to target cells. While lipid nanoparticles have improved delivery efficiency, ensuring targeted delivery to antigen-presenting cells remains a critical area of research. Non-specific distribution of mRNA can reduce efficacy and increase the risk of unintended immune responses.

The tumor microenvironment (TME) also poses a significant barrier. Tumors often create an immunosuppressive environment characterized by regulatory T cells, myeloid-derived suppressor cells, and inhibitory cytokines. This environment can inhibit the activation and function of immune cells, reducing the effectiveness of mRNA vaccines.

Additionally, **t**umor heterogeneity complicates treatment outcomes. Tumors consist of diverse cell populations with varying antigen expression profiles. Targeting a single antigen may not be sufficient to eliminate all tumor cells, leading to immune escape and disease recurrence.

The issue of immune tolerance is another critical challenge. Since many tumor-associated antigens are derived from self-proteins, the immune system may not recognize them as foreign. Overcoming this tolerance without inducing autoimmunity requires careful antigen selection and vaccine design.

Adverse immune reactions also need to be considered. While mRNA vaccines are generally safe, excessive activation of innate immune responses can lead to inflammation and reduced translation efficiency. Balancing immunogenicity and tolerability is essential for optimal vaccine performance.

From a manufacturing perspective, high production costs and scalability issues remain challenges. Although mRNA synthesis is relatively straightforward, the production of high-quality, clinical-grade mRNA and lipid nanoparticles requires specialized facilities and stringent quality control.

Regulatory challenges also exist, particularly for personalized mRNA vaccines, which require individualized manufacturing and rapid approval processes. Establishing standardized regulatory frameworks for such therapies is essential.

Finally, long-term data on efficacy and durability of immune responses are still limited. While early clinical trials show promising results, more extensive studies are needed to evaluate long-term outcomes and potential risks.

Addressing these challenges will require multidisciplinary efforts involving molecular biology, nanotechnology, immunology, and regulatory science. Continued innovation and research are essential to overcome these barriers and unlock the full potential of mRNA cancer vaccines.

7. Personalized mRNA Vaccines and Precision Oncology

Personalized mRNA cancer vaccines represent one of the most exciting advancements in modern oncology, aligning closely with the principles of precision medicine. Unlike conventional therapies that adopt a one-size-fits-all approach, personalized vaccines are tailored to the unique genetic profile of an individual's tumor.

The process begins with tumor sequencing, where next-generation sequencing (NGS) technologies are used to identify mutations in cancer cells. These mutations often result in the formation of neoantigens—novel proteins that are not present in normal cells and can be recognized as foreign by the immune system.

Once identified, these neoantigens are analyzed using bioinformatics tools to determine their immunogenic potential. Selected neoantigens are then encoded into synthetic mRNA, which is formulated into a vaccine specific to the patient.

This approach offers several advantages. First, it ensures high specificity, as the immune response is directed exclusively against tumor-specific mutations. Second, it reduces the risk of off-target effects and autoimmunity. Third, it enhances the likelihood of a strong immune response, as neoantigens are highly immunogenic.

Clinical studies have demonstrated promising results for personalized mRNA vaccines, particularly in melanoma. Patients receiving these vaccines have shown improved immune responses and reduced recurrence rates. When combined with immune checkpoint inhibitors, the efficacy is further enhanced.

However, personalized vaccines also present challenges. The process of sequencing, analysis, and vaccine production is time-consuming and costly. Rapid turnaround times are essential for clinical relevance, especially in aggressive cancers.

Advances in artificial intelligence (AI) and machine learning are helping to accelerate neoantigen prediction and vaccine design. These technologies can analyze large datasets to identify optimal targets and improve vaccine efficacy.

The integration of personalized mRNA vaccines into clinical practice represents a significant step toward precision oncology, where treatments are tailored to individual patients based on genetic, molecular, and immunological characteristics.

8. Future Perspectives and Conclusion

The future of mRNA cancer vaccines is highly promising, with ongoing advancements poised to overcome current limitations and expand their clinical applications.

One of the key areas of development is next-generation delivery systems. Researchers are exploring novel nanocarriers, including polymer-based nanoparticles, lipid-polymer hybrids, and exosomes, to improve targeting and efficiency.

Another important direction is the development of thermostable mRNA formulations, which can be stored at higher temperatures, reducing logistical challenges and improving global accessibility.

Combination therapies will play a crucial role in the future. mRNA vaccines are expected to be integrated with:

- Immune checkpoint inhibitors
- CAR-T cell therapy
- Oncolytic viruses
- Conventional therapies

Such combinations can enhance immune responses and overcome tumor resistance mechanisms.

Advancements in genomics, proteomics, and bioinformatics will further refine neoantigen identification and vaccine design. The use of AI-driven platforms will accelerate the development of personalized therapies.

From a regulatory perspective, frameworks must evolve to accommodate rapid, individualized treatments. Streamlined approval processes and adaptive clinical trial designs will be essential.

In conclusion, mRNA cancer vaccines represent a paradigm shift in cancer treatment. Their ability to provide safe, targeted, and personalized therapy positions them as a cornerstone of future oncology. While challenges remain, continued research, technological innovation, and clinical validation will pave the way for their widespread adoption

References

Pardi N, Hogan MJ, Porter FW, Weissman D. mRNA vaccines — a new era in vaccinology. *Nat Rev Drug Discov.* 2018;17(4):261–279.

Sahin U, Karikó K, Türeci Ö. mRNA-based therapeutics — developing a new class of drugs. *Nat Rev Drug Discov.* 2014;13(10):759–780.

Schlake T, Thess A, Fotin-Mleczek M, Kallen KJ. Developing mRNA-vaccine technologies. *RNA Biol.* 2012;9(11):1319–1330.

Kowalczyk A, Doener F, Zanzinger K, Noth J, Baumhof P, Fotin-Mleczek M, et al. Self-adjuvanted mRNA vaccines induce local innate immune responses. *J Immunol.* 2016;196(6):2563–2573.

Reichmuth AM, Oberli MA, Jaklenec A, Langer R, Blankschtein D. mRNA vaccine delivery using lipid nanoparticles. *Nano Lett.* 2016;16(12):7398–7404.

Kranz LM, Diken M, Haas H, Kreiter S, Loquai C, Reuter KC, et al. Systemic RNA delivery to dendritic cells exploits antiviral defence. *Nature.* 2016;534(7607):396–401.

Sahin U, Türeci Ö. Personalized vaccines for cancer immunotherapy. *Science.* 2018;359(6382):1355–1360.

Verbeke R, Lentacker I, De Smedt SC, Dewitte H. Three decades of messenger RNA vaccine development. *Nano Today.* 2019;28:100766.

Jackson NAC, Kester KE, Casimiro D, Gurunathan S, DeRosa F. The promise of mRNA vaccines. *NPJ Vaccines.* 2020;5:11.

Polack FP, Thomas SJ, Kitchin N, Absalon J, Gurtman A, Lockhart S, et al. Safety and efficacy of an mRNA COVID-19 vaccine. *N Engl J Med.* 2020;383(27):2603–2615.

Baden LR, El Sahly HM, Essink B, Kotloff K, Frey S, Novak R, et al. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. *N Engl J Med.* 2021;384(5):403–416.

Oberli MA, Reichmuth AM, Dorkin JR, Mitchell MJ, Fenton OS, Jaklenec A, et al. Lipid nanoparticle assisted mRNA delivery. *Nano Lett.* 2017;17(3):1326–1335.

Dolgin E. The tangled history of mRNA vaccines. *Nature.* 2021;597(7876):318–324.

Hou X, Zaks T, Langer R, Dong Y. Lipid nanoparticles for mRNA delivery. *Nat Rev Mater.* 2021;6(12):1078–1094.

Chen DS, Mellman I. Oncology meets immunology: the cancer-immunity cycle. *Immunity.* 2013;39(1):1–10.

Melief CJM, van Hall T, Arens R, Ossendorp F, van der Burg SH. Therapeutic cancer vaccines. *J Clin Invest.* 2015;125(9):3401–3412.

Ott PA, Hu Z, Keskin DB, Shukla SA, Sun J, Bozym DJ, et al. An immunogenic personal neoantigen vaccine. *Nature.* 2017;547(7662):217–221.

Keskin DB, Anandappa AJ, Sun J, Tirosh I, Mathewson ND, Li S, et al. Neoantigen vaccine generates intratumoral T cell responses. *Nature.* 2019;565(7738):234–239.

Granados-Riveron JT, Aquino-Jarquin G. Engineering of the mRNA translation machinery. *Mol Ther.* 2021;29(4):1388–1395.

Verbeke R, Lentacker I, De Smedt SC, Dewitte H. The dawn of mRNA vaccines. *Nat Rev Drug Discov.* 2021;20(10):705–706.

Buschmann MD, Carrasco MJ, Alishetty S, Paige M, Alameh MG, Weissman D. Nanomaterial

delivery systems for mRNA vaccines. *Vaccines.* 2021;9(1):65.

Huang Q, Zeng J, Yan J. mRNA vaccines for cancer immunotherapy. *Front Immunol.* 2021;12:795521.

Liu MA. A comparison of plasmid DNA and mRNA as vaccine technologies. *Vaccines.* 2019;7(2):37.

Li L, Petrovsky N. Molecular mechanisms for enhanced DNA vaccine immunogenicity. *Expert Rev Vaccines.* 2016;15(3):313–329.

Zhang C, Maruggi G, Shan H, Li J. Advances in mRNA vaccines. *Cell Mol Immunol.* 2019;16(6):549–550.