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mRNA Therapeutics Beyond COVID-19: Advances, Clinical Applications, Challenges and Future Perspectives.

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Abstract: *During the COVID-19 pandemic, messenger RNA (mRNA) vaccines were successfully developed, demonstrating the potential of mRNA technology as a flexible therapeutic platform. However, mRNA's uses go well beyond immunization against infectious diseases. The production of proteins, antigens, antibodies, or genome-editing components within target cells can be temporarily directed by therapeutic mRNA, opening up treatment options for cancer, metabolic and genetic disorders, cardiovascular diseases, and other ailments. The stability, translation efficiency, and tolerability of mRNA have been greatly enhanced by developments in nucleoside modification, sequence optimization, untranslated-region engineering, mRNA capping, purification, and lipid nanoparticle (LNP) delivery. One of the most active fields is cancer immunotherapy, especially with regard to combination therapies with immune checkpoint inhibitors and customized neoantigen vaccines. Concurrently, gene editing, mRNA-based protein replacement, and regenerative.*
Preclinical and clinical development of cardiovascular applications is advancing. Notwithstanding these developments, problems with tissue-specific delivery, stability, innate immune activation, toxicity, production, storage, repeated administration, and regulatory standardization still exist. The therapeutic potential of mRNA may be further expanded by novel strategies like self-amplifying RNA, circular RNA, targeted nanoparticles, computational sequence optimization, and personalized therapies. The main developments in mRNA design and delivery, therapeutic uses outside of COVID-19, clinical development, present constraints, and potential future paths of this quickly developing field are all outlined in this review

Keywords: mRNA therapeutics; messenger RNA; lipid nanoparticles; cancer vaccines; gene therapy; protein replacement; RNA delivery; personalized medicine.

I. INTRODUCTION

An intermediary molecule called messenger RNA (mRNA) transports genetic information from DNA to ribosomes, where it is translated into proteins. Despite being primarily investigated as a biological intermediate at first, mRNA is now a promising therapeutic platform thanks to developments in molecular biology, RNA engineering, and drug delivery technologies. mRNA therapeutics provide transient protein expression without nuclear entry or long-term host genome modification, in contrast to traditional gene therapy methods that insert DNA into cells [1–5].

Over several decades, the therapeutic idea of mRNA has evolved. Early research showed that exogenous mRNA could be inserted into cells and translated into useful proteins, but its practical use was constrained by instability, ineffective delivery, and undesired innate immune activation. The finding that adding modified nucleosides, especially pseudouridine, could significantly lower immune recognition and enhance translation of synthetic mRNA was a

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significant breakthrough [8,38]. Its therapeutic potential was further enhanced by later advancements in purification, sequence optimization, mRNA capping, untranslated-region engineering, and delivery systems [3,7,12,45].

An important turning point for mRNA technology was the COVID-19 pandemic. The platform could be designed, produced, and clinically assessed on an unprecedented timescale, as evidenced by the quick development and implementation of mRNA vaccines [7,10,11]. But this technology's importance goes beyond COVID-19 vaccination. mRNA-based strategies for cancer immunotherapy, infectious diseases, inherited and metabolic disorders, cardiovascular diseases, protein replacement, regenerative medicine, and gene editing are currently being studied [1,4,5,19,23,31,34].

The versatility of mRNA is one of its main benefits. Without altering the basic manufacturing concept, the same basic platform can be modified to encode various proteins or therapeutic molecules. Therefore, mRNA can be viewed as a programmable therapeutic system where the biological function is determined by the encoded sequence [2, 3]. Furthermore, in situations where transient protein expression is desired, like in vaccination, genome editing, cellular reprogramming, and regenerative applications, its transient nature may be beneficial [1,2].

However, there are other difficulties in transferring mRNA technology from vaccines to more general therapeutic uses. Improved tolerability, controlled protein expression, repeated administration, and precise delivery to specific organs or cell types are all necessary for many non-vaccine applications. While effective delivery to tissues outside the liver is still more challenging, conventional LNPs exhibit strong hepatic delivery after systemic administration [1,2,9,14–16]. Additional focus is needed on safety, immunogenicity, manufacturing consistency, storage stability, and regulatory standardization [13,17,18].

Thus, optimizing the mRNA molecule is only one aspect of the current development of mRNA therapeutics. Coordinated advancements in pharmacology, manufacturing, clinical development, delivery systems, and molecular engineering are needed. These advancements are covered in this review, with a focus on therapeutic uses of mRNA outside of COVID-19.

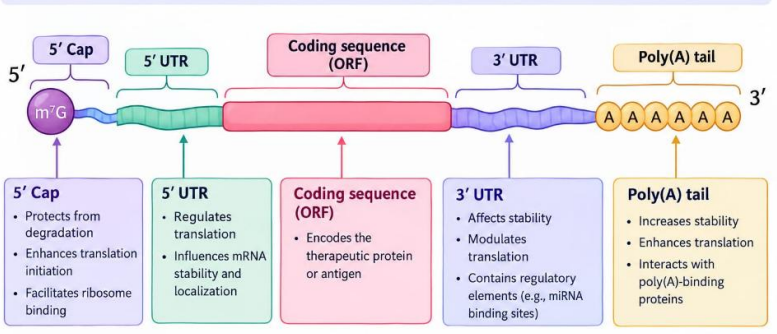
II. STRUCTURE, ENGINEERING AND DELIVERY OF THERAPEUTIC MRNA.

2.1 Structure of therapeutic mRNA.

The stability, translation efficiency, and biological activity of a typical therapeutic mRNA molecule are determined by a number of functional components. These comprise a poly(A) tail, 5′ cap, 5′ untranslated region (UTR), protein-coding open reading frame (ORF), and 3′ UTR [3,7,12]. By shielding the molecule from deterioration, the 5′ cap promotes mRNA stability and is necessary for effective translation initiation.

While the ORF contains the sequence encoding the intended therapeutic protein, the UTRs affect translation, intracellular localization, and mRNA stability. By interacting with poly(A)-binding proteins and other elements of the translational machinery, the poly(A) tail promotes mRNA stability and translation [3,7,12]. Optimizing the entire mRNA molecule is crucial rather than concentrating only on the coding sequence because every structural element can affect therapeutic performance.

Figure 1 . Structural organisation of therapeutic mRNA and functions of its major components.



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Adapted from refrences [3,7,12,45]

2.2mRNA engineering strategies.

To enhance its therapeutic efficacy, synthetic mRNA can be modified on several levels. By choosing codons that are effectively recognized by the host cellular machinery, codon optimization is frequently used to enhance translation. However, excessive sequence optimization should be carefully controlled as it may impact RNA structure [1, 3].

Translation and mRNA stability can be enhanced by optimizing the 5′ and 3′ UTRs. Stability and translational activity can also be influenced by choosing the right poly(A) tail length [2,12]. Because the cap structure influences translation initiation and shields mRNA from degradation, effective 5′ capping is another crucial factor [36].

Another important tactic is nucleoside modification. Protein production can be enhanced and innate immune sensor activation can be decreased by incorporating modified nucleosides like pseudouridine or N1-methylpseudouridine [8,38]. Because double-stranded RNA contaminants can trigger innate immune pathways and decrease translation, purification of in vitro-transcribed mRNA is also crucial [1,3,39].

Table 1. Major strategies used for optimization of therapeutic mRNA.

Engineering strategy.	**Major purpose.**
5′ cap optimization	Improves translation initiation and stability.
UTR optimization.	Enhances stability and translation.
Codon optimization.	Improves protein expression.
Nucleoside modification.	Reduces innate immune activation.
Poly(A) tail optimization.	Supports stability and translation.
dsRNA removal.	Reduces unwanted immune activation.
Sequence optimization.	Improves overall mRNA performance
Circular/saRNA approaches.	May increase duration or magnitude of expression.

Sources: [1–4, 8, 12, 20, 35, 36, 39].

2.3 Nucleoside modification and immune activation.

The creation of nucleoside-modified mRNA was one of the most significant developments in mRNA therapies. Innate immune receptors, such as Toll-like receptors and other RNA-sensing pathways, can be activated by unmodified RNA. This activation may cause inflammatory reactions and disrupt translation [3, 8]. Modified nucleosides have been shown by Karikó and associates to improve protein production while decreasing RNA recognition by innate immune receptors [8,38]. This finding served as a crucial basis for the subsequent creation of therapeutics and clinically effective mRNA vaccines.

Removing undesired double-stranded RNA produced during in vitro transcription can enhance translation and lower immune activation in addition to nucleoside modification [39]. For therapeutic applications where repeated administration may be necessary, these strategies are especially crucial.

2.4 Delivery systems for mRNA.

Delivery is still one of the main obstacles to therapeutic mRNA, despite advancements in mRNA engineering. mRNA is a big, negatively charged, and comparatively unstable molecule that can be broken down by enzymes. Therefore, in order to reach the right cells and release its cargo into the cytoplasm, it needs an efficient delivery system [3,40–42].

The most extensively studied non-viral mRNA delivery method is now lipid nanoparticles. Ionizable lipids, helper phospholipids, cholesterol, and polyethylene glycol-associated lipids are all present in a typical LNP [9,14]. These elements facilitate cellular uptake, support endosomal escape, and shield mRNA during delivery. LNPs can be absorbed by cells via endocytic pathways after administration.

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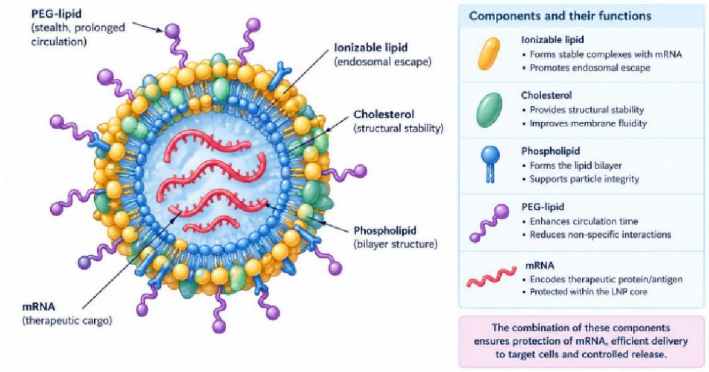
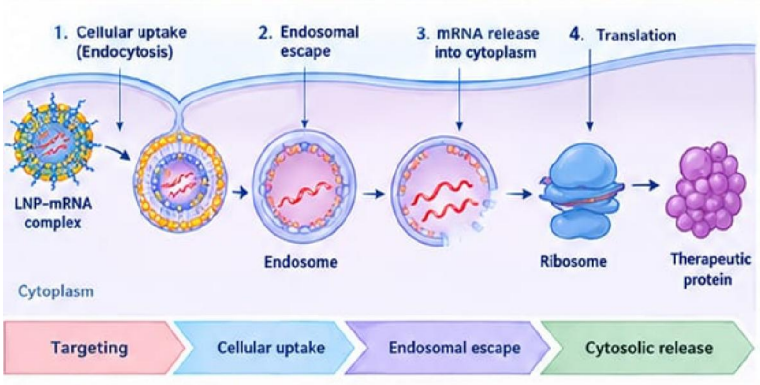
Ionizable lipids can encourage endosomal membrane disruption and release the mRNA into the cytoplasm once the nanoparticles have entered endosomal compartments. The intended therapeutic protein can then be produced by ribosomes translating the released mRNA [9,14–16]. However, after systemic administration, conventional LNPs exhibit a strong tendency toward hepatic accumulation. This limits the treatment of diseases requiring delivery to other organs, even though it is beneficial for liver-directed applications [1,2,9]. To accomplish extrahepatic delivery, scientists are creating tissue-targeted LNPs, ligand-modified nanoparticles, biodegradable lipids, and other delivery methods [14–18].

Figure 2. Structure of an mRNA loaded lipid nanoparticle (LNP).



Adapted from references [9,14-16,40-42]

Figure 3. Cellular uptake and intracellular mechanism of mRNA.



Adapted from references [9,14-16,40-42]

III. THERAPEUTIC APPLICATIONS OF MRNA BEYOND COVID-19.

Beyond COVID-19 vaccines, the therapeutic landscape of mRNA has grown significantly. Both infectious and non-infectious diseases are currently being developed. Hundreds of mRNA vaccine and therapeutic candidates are currently undergoing clinical development, with cancer accounting for a disproportionately large share of the non-communicable disease pipeline, according to a recent global assessment [34].

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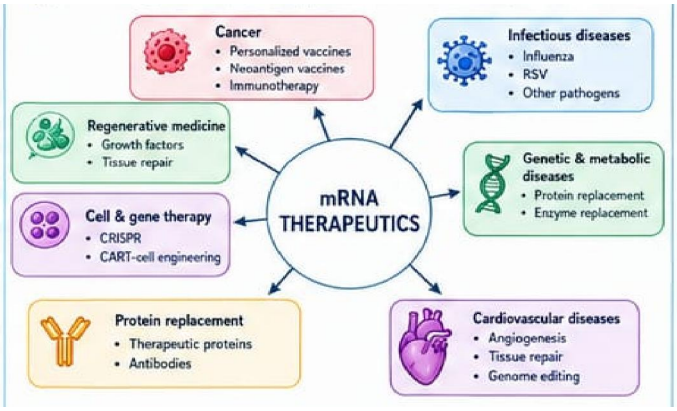
Figure 4. Major therapeutic applications of mRNA beyond COVID-19.



Adopted from refrences [1–5,19,23,31,33,34]

3.1 Infectious diseases.

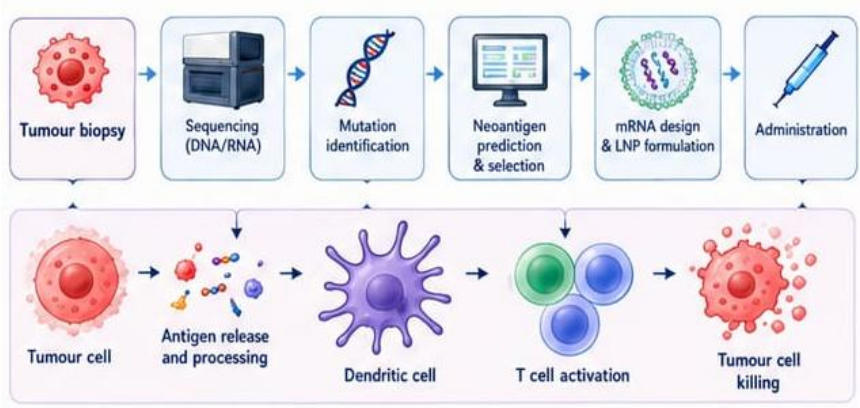
The clinical potential of mRNA was shown by COVID-19 vaccines, but the technology is also being studied against a number of other infectious diseases. The platform is appealing for diseases where traditional vaccine development can be slow because it can quickly alter an mRNA sequence in response to a pathogen [7,10,11]. mRNA vaccines against pathogens such as influenza, HIV, respiratory syncytial virus, tuberculosis, and other infectious diseases are being studied [11,34]. Because it can boost intracellular RNA amplification and possibly lower the quantity of RNA needed for an effective response, self-amplifying RNA is also being investigated [5,35].

Although many candidates are still in the early stages of clinical development, the global clinical-development landscape shows that mRNA candidates are being investigated across a wide range of communicable diseases [34].

3.2 Cancer immunotherapy.

One of the most significant non-infectious uses of mRNA technology at the moment is cancer. Therapeutic cancer vaccines are intended to elicit an immune response against tumours-associated or tumours-specific antigens, in contrast to traditional preventive vaccines [14,23–30].

Figure 5. Personalized mRNA cancer vaccine workflow.



Adapted from refrences [25-30,37]

Tumor-specific neoantigens, immunomodulatory proteins, and tumours-associated antigens can all be encoded by mRNA. The encoded antigen can be generated intracellularly and processed for presentation via major

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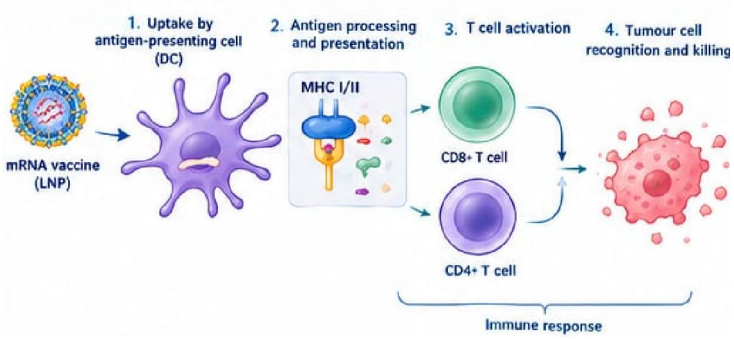
histocompatibility complex pathways after being delivered into antigen-presenting cells. Antigen-specific T cells that are able to identify and combat tumours cells may be activated as a result [14,23,24].

Customized cancer vaccinations The customized mRNA cancer vaccine is one of the most promising strategies. Genetic analysis of a patient's tumours tissue can reveal mutations that could produce neoantigens. Following computational prioritization, candidate neoantigens are added to a customized mRNA construct and given to the patient [27, 37].

Figure 6. Mechanism of mRNA cancer immunotherapy.



Adapted from refrences [23-30,37]

Tumor biopsy, sequencing, mutation identification, neoantigen prediction, vaccine design, mRNA-LNP formulation, administration, and activation of tumours-specific immune responses are the general steps involved in developing a customized mRNA cancer vaccine. Redrawn or modified from references [25–30, 37].

Combinations of immune checkpoint inhibitors and customized mRNA vaccines have been the subject of more and more clinical research. These combinations may improve T-cell responses and possibly get around some tumours immune evasion mechanisms [25–27].

Cancer accounts for a significant portion of the current mRNA therapeutic pipeline, according to recent clinical-development reviews [26,30,34].

Tumor heterogeneity, the discovery of clinically significant neoantigens, the timely production of customized vaccines, and efficient delivery to the tumours microenvironment are still obstacles.

3.3 Genetic and metabolic disorders.

For genetic diseases where the pathology of the disease is caused by a missing or defective protein, mRNA therapeutics provide an alternative approach. mRNA can temporarily supply instructions for making the functional protein rather than permanently altering the genome [19].

For conditions where temporary protein replacement may be therapeutically beneficial, this strategy is especially appealing. Metabolic disorders involving enzymes or other proteins that are challenging to treat with traditional recombinant protein techniques are among the examples being studied [2,19].

When permanent gene modification is undesirable, the transient nature of mRNA expression can also be advantageous. Delivery, durability of expression, and immunogenicity are crucial factors to take into account because many inherited disorders are chronic and may require repeated administration [1,2,19].

3.4 Protein replacement and therapeutic protein production.

Therapeutic proteins can be obtained intracellularly from mRNA. The target cells' own machinery translates the mRNA after it is delivered, enabling the transient synthesis of the desired protein. This method has been studied for proteins related to angiogenesis, tissue repair, metabolic pathways, and other biological processes [2].

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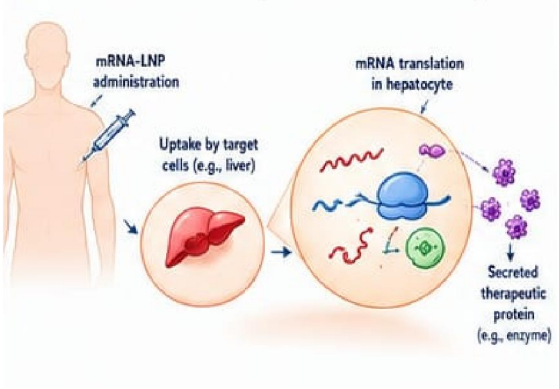
The application of vascular endothelial growth factor (VEGF) mRNA to stimulate angiogenesis and tissue repair is one prominent area. Therapeutic proteins may be able to act within a limited tissue and time frame through localized delivery, which could lower systemic exposure [2].

Antibodies and other complex proteins can also be encoded by mRNA. Although effective tissue targeting and expression control remain significant challenges, this offers an alternative to producing and frequently administering recombinant proteins [2]

Figure 7. mRNA mediated protein replacement therapy.



Adapted from refrences [2,19,21,23,31,33]

3.5 Cardiovascular applications and regenerative medicine.

Another new use of mRNA technology is in cardiovascular disease. The expression of proteins involved in angiogenesis, tissue repair, cardiac function, and genome editing through mRNA has been studied [31, 32].

Because some therapeutic proteins may be helpful for a brief time during tissue repair, the transient expression properties of mRNA may be especially helpful in regenerative medicine. For instance, VEGF mRNA has been studied for tissue repair and vascular regeneration [2,31].

Additionally, mRNA is being researched as a tool for cellular engineering and genome editing. mRNA can temporarily encode genome-editing proteins like CRISPR-associated nucleases instead of providing a permanent genetic sequence [2,4].

While delivery to the right tissues and preventing off-target effects are still major concerns, this may lessen extended exposure to genome-editing components.

3.6 Emerging applications: genome editing, cell therapy and regenerative medicine.

Because of its adaptability, mRNA can encode proteins that alter the behavior of cells. Transient expression of transcription factors, genome-editing proteins, chimeric antigen receptors, and other molecules involved in cellular engineering are among the applications being studied [2–5].

Therefore, mRNA-based strategies could be used in addition to traditional gene and cell therapies. When extended expression is not required or desired, their fleeting nature may be beneficial. New RNA formats could increase these opportunities even more. Circular RNA is being investigated as a potentially more stable RNA format, while self-amplifying RNA can replicate intracellularly and possibly produce higher levels of protein from smaller doses [5,35,40].

IV. CLINICAL DEVELOPMENT OF MRNA THERAPEUTICS.

The success of COVID-19 vaccines has significantly accelerated the clinical development of mRNA therapeutics. Beyond traditional preventive vaccination, the development pipeline now encompasses a number of therapeutic

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categories. Therapeutic mRNA applications were divided into four categories in a recent clinical-development analysis: vaccines, protein replacement, therapeutic antibodies, and cell and gene therapies [5].

244 mRNA vaccine and therapeutic candidates were found in a broader global assessment published in 2026. Of these, 123 were for communicable diseases and 121 were for non-communicable diseases, with cancer making up a significant portion of the latter group [34].

Despite the field's rapid growth, the majority of candidates were still in the early stages of clinical development.

Table 2. Representative therapeutic applications of mRNA.

Application	Therapeutic strategy	Development status
Infectious diseases	Antigen-encoding mRNA vaccines	Clinical
Cancer	Personalized/shared-antigen vaccines	Clinical
Genetic disorders	Protein replacement	Preclinical/clinical
Cardiovascular disease	Angiogenic and regenerative proteins	Preclinical/clinical
Genome editing	Transient CRISPR component expression	Preclinical/clinical
Cell therapy	CAR/TCR-related engineering	Preclinical/clinical
Regenerative medicine	Temporary growth-factor expression	Preclinical/clinical

Sources: [2,5,19,23,31–34].

Table 3. Selected examples of mRNA therapeutic development.

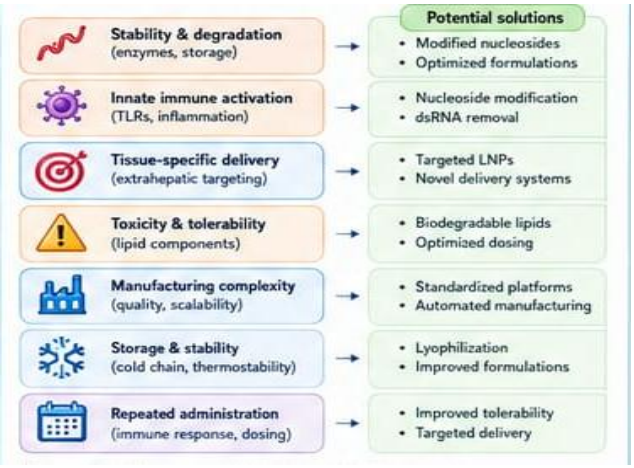
Area.	Representative approach	Main objective
Cancer.	Personalized neoantigen mRNA vaccines.	Tumour-specific immune activation.
Cancer	mRNA vaccine + checkpoint inhibitor.	Enhance antitumour immunity.
Genetic disease.	Protein-encoding mRNA.	Temporary protein replacement.
Cardiovascular disease.	VEGF and other therapeutic proteins.	Angiogenesis/tissue repair.
Genome editing.	mRNA-encoded CRISPR components.	Transient genome modification.
Infectious diseases.	Pathogen-antigen mRNA.	Preventive or therapeutic immunity.

Sources: [2,5,19,23–27,31,34,37].

mRNA is no longer limited to immunization. Nonetheless, compared to early-stage programs, there are still far fewer late-stage candidates [5,34]. This emphasizes the need for additional clinical validation in relation to tissue-specific delivery, repeated administration, dose optimization, and long-term safety.

V. CHALLENGES AND LIMITATIONS.

Figure 8. Challenges and limitations pf mRNA therapeutics.



Adapted from [1-3,13-18,20-22]

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Even with significant advancements, a number of obstacles need to be removed before mRNA treatments can be widely used in clinical settings.

5.1 Stability and degradation.

mRNA is naturally vulnerable to ribonuclease degradation. While stability is increased by structural engineering, nucleoside modification, and LNP encapsulation, it is still difficult to preserve molecular integrity during production, storage, transportation, and administration [1,3,9].

5.2 Innate immune activation.

Inflammatory reactions and decreased translation can result from unwanted activation of innate immune pathways. Although this problem has been greatly resolved by modified nucleosides and purification techniques, immune activation is still important, especially for repeated administration [8,13,38,39].

5.3 Tissue-specific delivery.

Achieving effective delivery of therapeutic mRNA to the targeted tissue or cell type may be the biggest obstacle. Although extrahepatic targeting is still more challenging, LNPs are very effective for hepatic delivery [1,2,9,14–16]. Thus, targeted LNPs, ligand-based targeting, biodegradable ionizable lipids, hybrid nanoparticles, and other delivery systems are the main topics of current research [14–18].

5.4 Toxicity and tolerability.

An mRNA delivery system's constituent parts may exacerbate inflammatory reactions or have other negative consequences. Because both the RNA and the delivery vehicle can affect immune responses, repeated administration may be especially difficult [13,17]. Future mRNA treatments will therefore need to carefully optimize dosage, formulation, administration route, and treatment frequency.

Table 4. Major challenges associated with mRNA therapeutics and potential solutions.

Challenge.	Potential approach.
RNA instability.	Sequence/UTR optimization, modified nucleosides, improved formulations.
Innate immune activation.	Nucleoside modification and dsRNA purification.
Poor extrahepatic delivery.	Targeted LNPs and novel delivery systems.
Endosomal trapping.	Improved ionizable lipids.
Toxicity.	Biodegradable lipids and optimized dosing.
Repeated administration.	Improved tolerability and targeted delivery.
Manufacturing complexity.	Scalable and standardized production.
Cold-chain requirements.	Thermostable and lyophilized formulations.
Personalized manufacturing.	Automated and rapid production platforms.

Sources: [1–3,9,13–18,20–22,40–42].

5.5 Manufacturing challenges.

RNA sequence integrity, capping efficiency, poly(A) tail characteristics, purity, residual DNA, dsRNA contaminants, and LNP properties are among the quality attributes that must be controlled for therapeutic mRNA production [3,20,22]. For personalized therapies, where manufacturing needs to be quick enough to fit the patient's treatment schedule, scaling production while preserving batch-to-batch consistency is especially crucial.

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5.6 Storage and stability.

For certain mRNA formulations, temperature sensitivity is still a crucial factor. Future reliance on stringent cold-chain conditions may be lessened by advancements in formulation, lyophilization, and thermostable delivery systems [2,20].

5.7 Repeated administration.

Unlike preventive vaccinations, which may be given relatively infrequently, many chronic diseases may require repeated dosing. Concerns about immune activation, delivery-system tolerability, and accumulation may worsen with repeated exposure [1,2,13].

VI. REGULATORY AND MANUFACTURING CONSIDERATIONS.

The need for suitable manufacturing and regulatory frameworks has increased due to the quick clinical development of mRNA technology. Quality evaluation must take into account both the RNA molecule and its delivery system because mRNA therapeutics have several functional components. Sequence identity, RNA integrity, 5′ capping, poly(A) tail characteristics, purity, residual impurities, particle size, encapsulation efficiency, and release characteristics are all significant quality attributes [3,20,22]. Because in vitro transcription offers a cell-free production method that can be tailored to various sequences, mRNA manufacturing is appealing. Personalized treatments and quickly evolving infectious disease targets benefit greatly from this [1,2].

However, because each patient's product may have a different sequence, personalized mRNA products present additional manufacturing and regulatory challenges. For broader clinical implementation, standardized manufacturing platforms, automated production, validated analytical techniques, and suitable regulatory frameworks will be crucial. The importance of manufacturing capacity outside of high-income countries is further highlighted by the expanding global mRNA-development landscape. In order to adapt mRNA technology to diseases relevant to various populations, recent analyzes highlight the necessity of technology transfer and regional manufacturing capabilities [34].

VII. FUTURE PERSPECTIVES.

Improvements in the mRNA molecule and its delivery mechanism will probably be crucial for the future of mRNA therapeutics. Extrahepatic and cell-specific delivery is one important approach. Although targeted nanoparticles that can specifically target immune cells, tumors, muscle, the heart, or other tissues could significantly increase the therapeutic range of mRNA, current LNP technology offers effective liver delivery [14–18]. The creation of next-generation RNA formats is another crucial field. While circular RNA may offer more molecular stability, self-amplifying RNA may enable greater protein production from smaller amounts of RNA [5,35].

These technologies have the potential to expand therapeutic applications and lower dosage requirements.

Optimized mRNA sequences, neoantigen selection, LNP formulation, and customized cancer vaccines may all benefit from artificial intelligence and computational design [23, 29, 35]. Combining immune checkpoint inhibitors and other immunotherapies with customized mRNA vaccines may prove to be a significant cancer treatment approach [25–30,37].

Simultaneously, efforts to find common tumours antigens may eventually lead to more scalable, off-the-shelf, or partially customized cancer vaccines. Improved tissue targeting may enable mRNA to temporarily express therapeutic proteins in genetic and cardiovascular diseases without permanently altering the genome [19,31,32]. Another significant frontier is manufacturing. Platforms for automated, modular, and scalable production could shorten production times and increase access to customized treatments. Enhancements in lyophilization and thermostability may also make distribution and storage easier [2,20].

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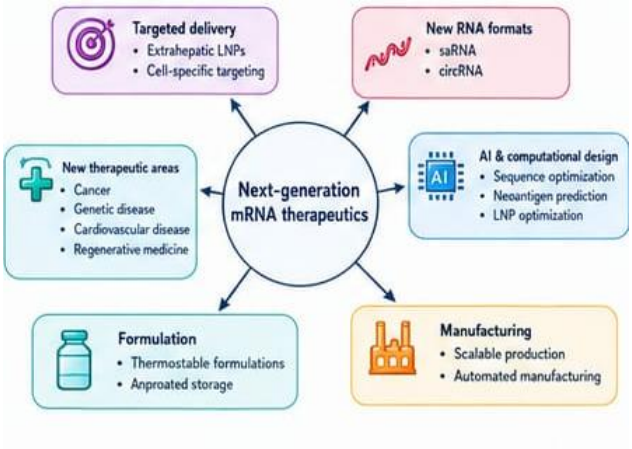
Figure 9. Future perspectives in mRNA therapeutics.



Aapted from refrences [2,5,14-20,31,35,40]

VIII. CONCLUSION.

From an experimental molecular biology concept, mRNA technology has developed into a therapeutic platform with clinical relevance. Rapid mRNA design, production, and clinical translation are feasible, as evidenced by the COVID-19 vaccine's success. However, the technology's wider potential includes cancer, genetic and metabolic diseases, cardiovascular disorders, protein replacement, regenerative medicine, and genome editing. Numerous early mRNA therapeutics limitations have been addressed by developments in nucleoside modification, sequence engineering, purification, capping, and LNP formulation. However, there are still significant obstacles to effective tissue-specific delivery, repeated administration, toxicity, manufacturing, stability, and regulatory standardization.

While applications in genetic and cardiovascular diseases are growing, cancer immunotherapy and customized neoantigen vaccines are currently among the most active areas of clinical development. The platform's therapeutic versatility may be further enhanced by emerging technologies like targeted LNPs, self-amplifying RNA, circular RNA, computational design, and automated manufacturing. The integration of molecular engineering, sophisticated drug delivery systems, clinical pharmacology, manufacturing science, and personalized medicine will ultimately determine the future of mRNA therapeutics. Instead of being mainly connected to COVID-19 vaccination, mRNA may become a more comprehensive therapeutic platform with further advancements in these fields.

IX. LITERATURE SURVEY

To understand how mRNA therapeutics have developed and where they might go beyond COVID-19, I reviewed research articles and reviews covering their design, delivery, clinical uses, and limitations.

The groundwork was laid by Karikó et al. (2005), who showed that modifying nucleosides reduces the recognition of RNA by Toll-like receptors, which made therapeutic mRNA easier for the body to tolerate. Three years later, Karikó et al. (2008) found that incorporating pseudouridine made mRNA more stable and improved its translation into protein. Together, these findings underpin modified mRNA technology.

On the vaccine side, Jackson et al. (2020) examined the promise of mRNA vaccines, along with the practical difficulties of developing them and manufacturing them at industrial scale. Delivery is a separate challenge. Hou et al. (2021) reviewed lipid nanoparticles (LNPs), explaining how they protect mRNA from degradation and carry it into cells.

Several authors have pointed to how broadly mRNA could be applied. Rohner et al. (2022) described its potential across many disease areas, and Qin et al. (2022) likewise noted its versatility for infectious diseases, cancer, genetic disorders, and other conditions. In cancer specifically, Vishweshwaraiah and Dokholyan (2022) reviewed mRNA

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vaccines in immunotherapy, particularly their ability to provoke immune responses against tumor-associated antigens. Sahin et al. (2017) provided early evidence for personalized RNA-based cancer vaccines by testing whether they could trigger immune responses against mutations unique to each patient's tumor.

More recent work continues to move beyond infectious disease. Parhiz et al. (2024) considered the wider prospects for mRNA therapeutics outside COVID-19 vaccines. Studies on genetic diseases also point to the possibility of producing functional proteins in people whose own proteins are defective or missing.

Taken together, the literature presents mRNA as a flexible platform with potential in cancer immunotherapy, infectious disease, genetic and metabolic disorders, and protein replacement therapy. Still, significant obstacles remain, including stability, targeted delivery, immune activation, toxicity, manufacturing, storage, and repeated dosing. More research and clinical testing will be needed before the safety, efficacy, and long-term usefulness of mRNA therapeutics can be established across different diseases.

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