Technology and Responsibility Report: mRNA Technology

Executive Summary - Gil

Traditional vaccines train the immune system by weakening or inactivating whole pathogens. mRNA vaccines deliver genetic instructions that cells translate into viral proteins. Lipid nanoparticles protect mRNA from degradation before it reaches cells, while nucleoside modification prevents the immune system from destroying the foreign RNA before translation. mRNA degrades after translation, making antigen production transient. Whether transience reduces safety risks remains uncertain.

Sequence design can begin within days of a genome being published, whereas traditional vaccines often spend months isolating and culturing the virus. Full development still takes months because manufacturing and trials cannot be compressed.

Early-phase trials are testing the platform in cancer immunotherapy by encoding tumor-specific antigens, in gene therapy by delivering functional copies of defective genes, alongside genome editing by combining mRNA with CRISPR. All three applications remain experimental with limited efficacy data.

Six decades of foundational work in mRNA biology and delivery systems enabled the COVID-19 timeline. Katalin Karikó and Drew Weissman's 2005 discovery of pseudouridine modification was central to this progress. When the SARS-CoV-2 genome was published in January 2020, the Pfizer-BioNTech vaccine reached Emergency Use Authorization in December 2020, eleven months later. Karikó and Weissman received the Nobel Prize in Physiology or Medicine in 2023.

Rapid deployment exposed pre-existing gaps in access and oversight. High-income countries secured early supplies while many low-income countries waited many months after US and EU approvals, reflecting dependence on a few patent holders and manufacturing sites. Vaccines were deployed before long-term safety data were available. Post-marketing surveillance later detected myocarditis in young males alongside anaphylaxis and rare neurological events, with long-term effects still unknown. Because the same tools that allow rapid vaccine redesign could also speed the development of engineered pathogens or immune-suppressing agents, the platform raises dual-use concerns.

Reducing harm requires addressing inequities at every stage from testing through production to distribution. Diversifying trial recruitment and strengthening post-marketing surveillance are starting points. Manufacturing partnerships with facilities in the Global South reduce dependence on concentrated producers, improving supply chain resilience and access speed during future outbreaks. Intellectual property waivers alongside WHO technology transfer and pandemic treaties can make vaccine access faster and more equitable in future crises.

Introduction - John

In order for our genetic material to create the tools that it codes for, DNA must first be transcribed into RNA (mRNA) inside the nucleus, and then this RNA must be translated into

protein in the cytoplasm. These proteins can then carry out a variety of functions within and outside of the cell. This process can be mimicked using DNA or RNA introduced from outside of the cell. Viruses introduce their genetic material into host cells and allow the host machinery to transcribe/translate this material into proteins.

Viral infections can affect many parts of the body, such as the respiratory system, digestive system, and the nervous system. A virus may enter the body through the respiratory tract, the skin and even the eyes. Once viral proteins bind to the surface proteins of human cells, the virus will begin injecting its DNA or RNA. After successful infection of a cell, the virus may spread to the rest of the body via the bloodstream or nerve endings. The symptoms that occur during infection are the body's attempt to kill the virus.

To alert immune cells to infection, the infected cells can present fragments of their proteins to immune cells using MHC class I molecules. The immune cells can "memorize" the virus protein fragment (antigen) and recruit other immune cells to kill the virus itself as well as all infected cells. Once an infection is cleared, most of the activated immune cells will die, but some will persist as memory T or B cells. One way to combat viral infection is through vaccination. The previous generation of vaccines contain a weakened or inactive version of the virus antigen, which will lead to an immune response without an accompanying infection.

The newest development regarding vaccines is the mRNA vaccine which introduces mRNA that codes for the virus antigen into the patient. The antigen itself isn't dangerous, so the immune system is able to recognize this protein fragment and develop memory immune cells without the associated symptoms of virus infection. There are several advantages to mRNA vaccines over traditional vaccines, such efficacy and manufacturing and scaleup efficiency.

In this report, we will review the history and current state of mRNA vaccines as well as discuss the ethical and societal concerns surrounding this technology. Finally, we will provide recommendations that confront concerns, manage the risks and maximize the benefits of this technology.

Historical Development and Current State - **Bo Hu**

The foundational (famous) Central Dogma of Molecular Biology, first proposed by Francis Crick in 1958, who also co-discovered the iconic (more famous) double-helix structure of DNA, describes the flow of genetic information: from DNA to RNA, and then to protein [1]. This foundational principle explains how genetic information is stored in DNA, transcribed into mRNA, and then translated into functional proteins, as shown in Fig.1.

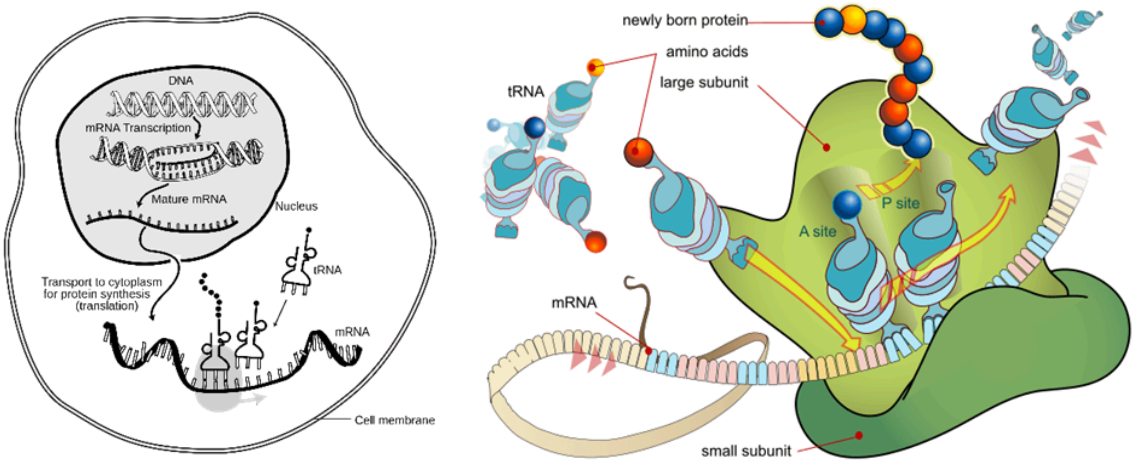


Fig. 1 Central Dogma of Molecular Biology and mRNA [2].

During the early 1960s, scientists gradually clarified the role of message Ribonucleic Acid (mRNA), discovering that it is a single-stranded RNA that carries genetic information and guides protein synthesis, acting as a bridge between genes and proteins. Jacob and Monod discovered that proteins are synthesized on ribosomes in the cytoplasm, suggesting a link between the chromosomes in the nucleus and the ribosomes, indicating a mechanism for transferring genetic information from the nucleus to the cytoplasm. However, this did not answer how genetic information is translated into proteins. Since ribosomal RNA did not have different types of RNA templates, it was ruled out as a carrier of genetic information, suggesting the presence of other RNA molecules in the cell to carry genetic messages. Shortly thereafter, Jacob and Jacques Monod proposed the mRNA hypothesis, suggesting the existence of a special RNA synthesized directly from DNA, complementary to the gene sequence, which is then transported to the cytoplasm as a template for protein synthesis. To test this hypothesis, Brenner et al. conducted experiments and discovered that after infecting E. coli with a bacteriophage, virus-specific RNA was synthesized and briefly bound to the ribosomes, validating the existence of mRNA [3-4].

Due to the instability and susceptibility to degradation of mRNA, for a period, there was a lack of effective methods to deliver it into specific target cells and ensure the production of sufficient amounts of the target protein, which limited the progress of related research. Until 1978, Dimitriadis et al. discovered that lipid-based delivery systems could effectively encapsulate mRNA, protect it from enzymatic degradation, and achieve high encapsulation efficiency. The functional lipid components in these carriers, which typically carry a positive charge, electrostatically interact with the negatively charged mRNA, facilitating fusion with the target cell membrane and enabling mRNA delivery. For the first time, scientists successfully used liposomes to deliver mRNA encoding rabbit globulin to mouse lymphocytes, resulting in the production of functional protein, and this laid the foundation for future mRNA delivery technologies [5].

Although mRNA technology made significant progress afterward, due to technological limitations, mRNA was primarily extracted from biological sources for research purposes, and

few researchers considered it a potential medical product. In 1984, Krieg et al. used RNA polymerase extracted from viruses to synthesize biologically active mRNA in the lab. They then injected the synthetic mRNA into frog eggs, demonstrating that it functioned the same as natural mRNA. At that time, they viewed synthetic mRNA as a tool for studying gene function [6].

A breakthrough came in the early 1990s, when Wolff et al. and Martinon et al. injected naked or lipid-encapsulated mRNA into mouse muscle, demonstrating for the first time that it could express active protein in vivo, marking the birth of mRNA-based therapy [7-8]. However, mRNA is a molecule that is difficult to manipulate, far less stable than DNA or proteins, and is easily degraded. More importantly, even if mRNA can be stably extracted and injected, it may trigger an immune response, like how the body reacts to viral invasion. This poses significant safety risks, creating new challenges for this therapeutic approach. With the development of nanoscience and nanotechnology, lipid nanoparticles (LNPs) began to emerge. During the same period, Pieter et al. started researching macromolecule drug delivery and discovered that lipid nanoparticles could effectively deliver mRNA to the liver and produce proteins. It wasn't until years later that the key role of LNPs in mRNA technology was widely recognized [9].

In addition to the instability of mRNA and the challenges of delivery into cells, another issue is its susceptibility to being recognized and cleared by the body's immune system. As a result, researchers have been seeking technological breakthroughs. In 2005, Katalin Karikó and Drew Weissman made a landmark discovery in the modification of mRNA. They demonstrated that substituting uridine with pseudouridine in synthetic mRNA not only shielded it from immune system recognition but also significantly enhanced its protein expression capacity, as shown in Fig. 2. This pivotal finding addressed a major obstacle in the clinical application of mRNA and laid the foundation for the development of mRNA-based therapeutics [10].

Katalin Karikó and Drew Weissman’s findings marked the beginning of the clinical application of mRNA and paved the way for the early commercialization of mRNA technology. Between 2000 and 2010, the commercial potential of mRNA technology began to be recognized. During this period, major pharmaceutical companies started to invest in mRNA technology. In 2008, both Novartis and Shire established mRNA-focused research divisions. Novartis focused on vaccine development, while Shire concentrated on therapeutics. Additionally, the well-known mRNA leaders CureVac, BioNTech, and Moderna were founded in this decade, each contributing to the development and advancement of mRNA technology [12].

As mentioned earlier, Pieter Cullis and his team made pioneering contributions to the use of LNPs in the mRNA field in the 1990s, but the specific mechanism of LNPs as mRNA carriers has yet to be fully elucidated. In 2015, Pardi et al. systematically characterized the expression kinetics of nucleoside-modified mRNA delivered in LNPs via various administration routes, demonstrating that LNPs could effectively protect mRNA from degradation while facilitating its efficient cellular uptake and protein expression [13].

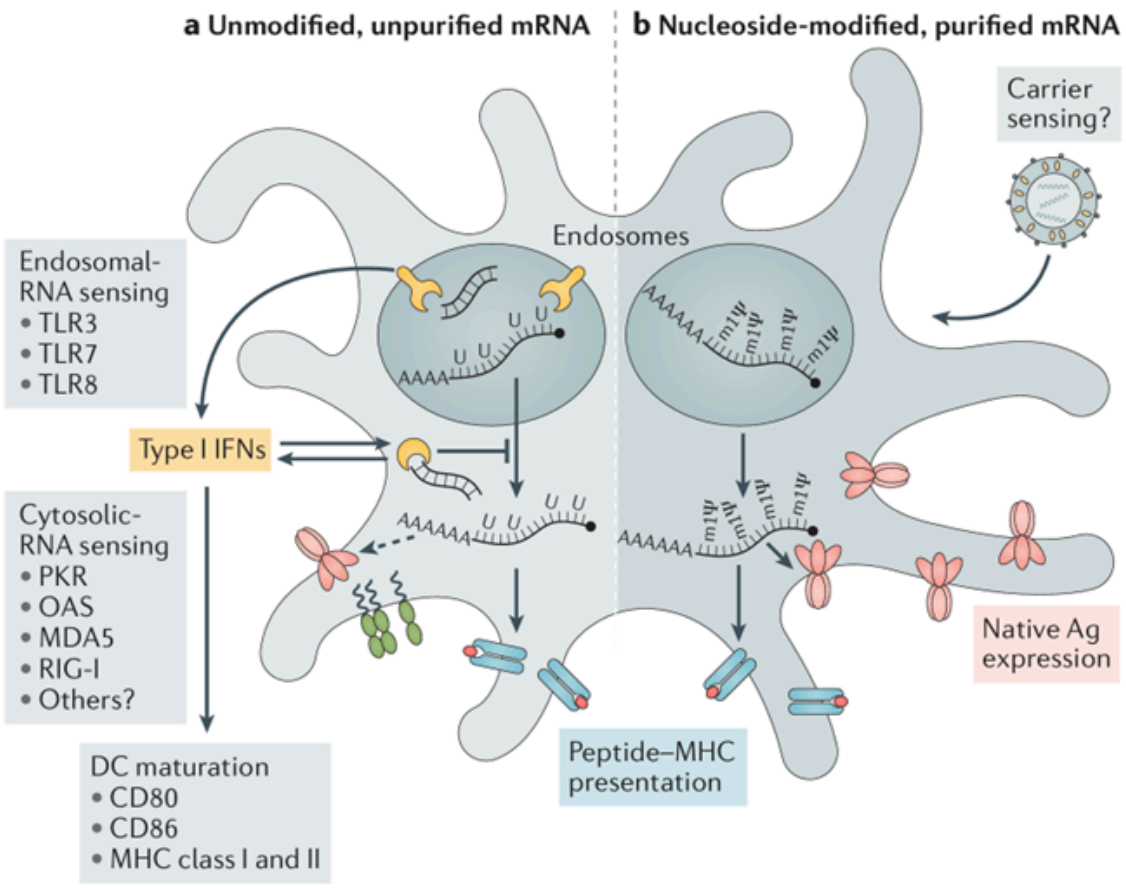


Fig. 2 Innate immune sensing of mRNA vaccines [11].

At this point, the two most formidable challenges in the development of mRNA therapies were overcome with the resolution of the mRNA modification issue and the application of LNP technology. However, despite these technical breakthroughs, the commercialization of this technology remained a significant challenge. As of 2020, no mRNA vaccine or therapeutic has been officially approved for market use. Among all the companies developing mRNA technology, Moderna was considered the most promising. However, by early 2020, although Moderna had nine mRNA vaccine candidates for infectious diseases in clinical trials, none had achieved significant success, with only one advancing to larger-scale trials.

The global COVID-19 pandemic erupted in 2020, posing a significant threat to all of humanity. However, it also presented a turning point for the development of mRNA technology. In response to the sudden outbreak, Moderna acted swiftly, developing a prototype vaccine within days of the publication of the SARS-CoV-2 genome sequence. The company then collaborated with the National Institute of Allergy and Infectious Diseases (NIAID) to conduct mouse studies and human trials, all within less than 10 weeks. Similarly, BioNTech mobilized its entire team. In March 2020, BioNTech partnered with Pfizer to complete a record-breaking journey from the first human trials to emergency use authorization in under 8 months. By December 2020, the Pfizer/BioNTech COVID-19 vaccine, the world's first mRNA vaccine, received Emergency Use

Authorization from the FDA, marking the beginning of mass vaccination efforts globally. Fig. 3 vividly captures the thrilling, high-stakes race against time by showing the timeline depicting the key milestones in the accelerated development of the SARS-CoV-2 mRNA vaccines (Moderna and BioNTech-Pfizer) in a single year (2020), from the publishing of the genomic sequence (Jan. 12) to receiving Emergency Use Authorization (EUA) in the US (Dec.) [14].

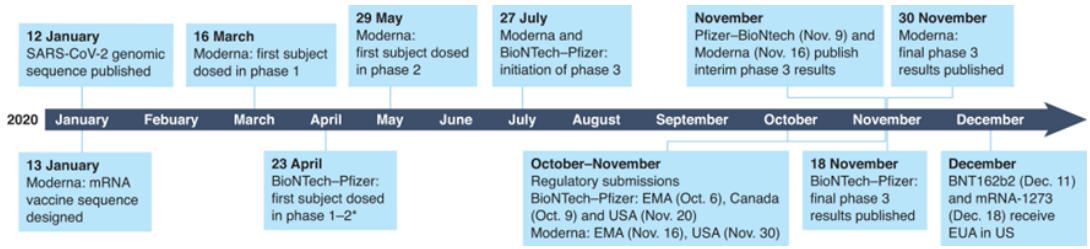


Fig. 3 2020 timeline showing rapid development of mRNA vaccines against SARS-CoV-2 [14].

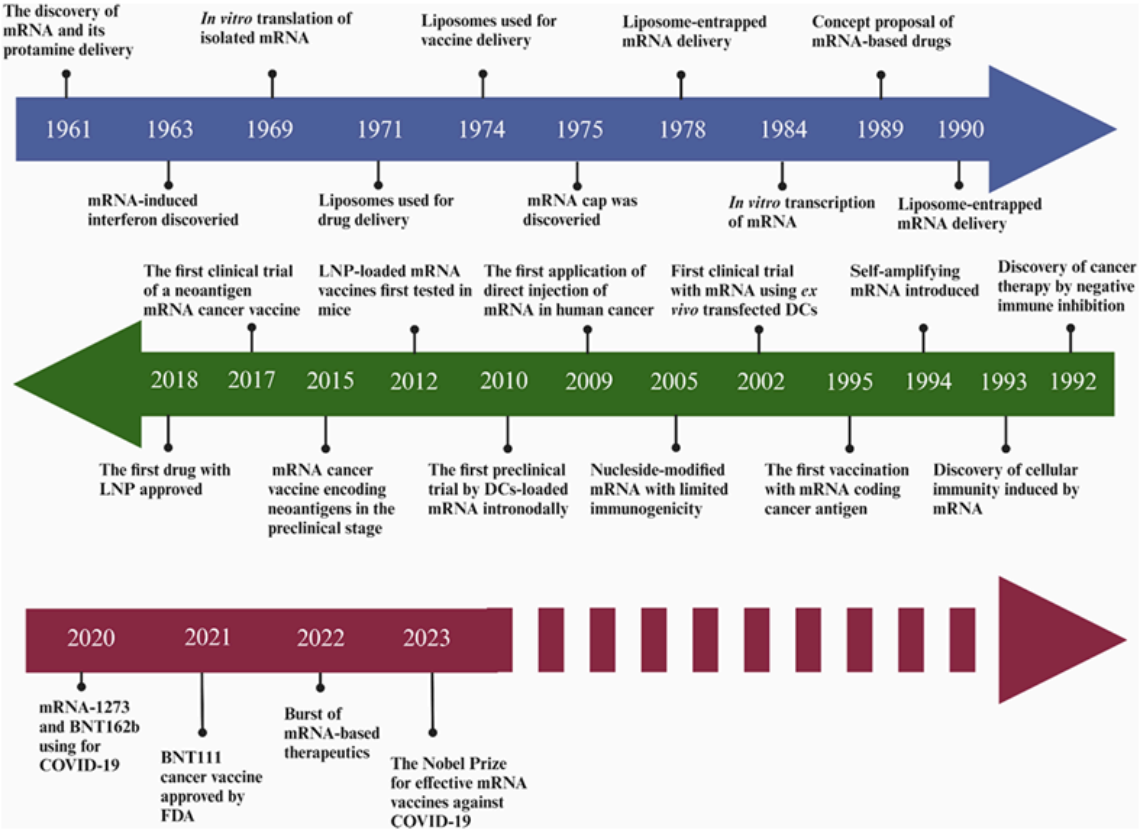


Fig. 4 Timeline of representative discoveries and breakthroughs in mRNA technology [15].

As the pandemic gradually recedes, Katalin Karikó and Drew Weissman eventually have been awarded the Nobel Prize in Physiology or Medicine in 2023 for their groundbreaking contributions to mRNA technology. Their discovery of how to modify mRNA to evade immune system recognition paved the way for the development of mRNA vaccines. Their research not

only laid the foundation for the rapid development of COVID-19 vaccines but also opened broad prospects for the innovation of future vaccines and therapies.

Fig. 4 illustrates this long and legendary journey of the development of mRNA technology, spanning over sixty years [15]. Starting with the discovery of mRNA in 1961, early research focused on basic science and the exploration of delivery systems, such as the use of liposomes. Subsequently, the focus shifted to applied research, particularly in the field of cancer vaccines. The 2005 discovery that nucleoside modification could limit immunogenicity was a crucial technical breakthrough, and, coupled with the maturation of the LNP delivery system, laid the foundation for its subsequent success. Finally, in 2020, mRNA technology achieved a groundbreaking commercial application in the fight against COVID-19 and subsequently earned the Nobel Prize in 2023, solidifying its core position in modern medicine.

In the post-pandemic era, mRNA technology has become a breakthrough in the field of biomedicine, showcasing tremendous potential. In addition to the successful application of COVID-19 vaccines, mRNA technology is rapidly expanding into cancer immunotherapy, the treatment of genetic diseases, and the development of antiviral vaccines. Numerous pharmaceutical companies and research institutions around the world are accelerating their exploration of mRNA, driving its wider use in medicine. The success of the mRNA COVID-19 vaccines has sparked industry expectations for this technology, leading to a surge in capital investment and prompting many mRNA-focused companies to increase their research and development efforts.

Currently, mRNA technology has extended beyond vaccine development into cancer immunotherapy. Scientists are customizing mRNA to activate the immune system of patients, enabling it to precisely target and attack cancer cells. This personalized approach not only offers new hope for cancer patients but also has the potential to revolutionize cancer treatment. Additionally, mRNA's potential in gene therapy is beginning to emerge, with clinical trials already exploring how mRNA can be used to repair or replace defective genes, offering the possibility of curing genetic disorders, particularly those with no effective treatments available.

With the continued optimization of mRNA production and delivery technologies, it is expected that this technology will play an increasingly important role in future medicine and drug development. In the field of vaccine development, mRNA technology will be key in addressing emerging viruses and rapidly spreading diseases. Meanwhile, the combination of mRNA technology with other cutting-edge technologies, such as CRISPR gene editing, has opened up even more possibilities for medical innovation. For example, researchers are exploring ways to combine CRISPR and mRNA to precisely repair genes, thereby providing more effective treatments for genetic diseases.

As we look toward the future, the application of mRNA technology will continue to expand and could lead to a new medical revolution. As production and delivery technologies improve, mRNA will play an increasingly critical role in various therapeutic fields, including antiviral, anticancer, and genetic disease treatments, offering new hope for global health.

Ethical and Societal Analysis-Lin Yang

4. Ethical and Societal Analysis

This section analyzes the ethical and societal implications of mRNA vaccine technology by focusing on three critical issues: (i) uncertainty in risk–benefit assessment, (ii) equity in access and distribution, and (iii) systemic pressures shaping research, regulation, and public communication.

4.1 Risk–Benefit Uncertainty and Responsible Science

One of the most significant ethical issues raised by mRNA vaccines is uncertainty in long-term risk–benefit evaluation. From the perspective of Resnik's principles, this issue highlights a tension between beneficence and non-maleficence. On one hand, mRNA vaccines provided substantial and immediate societal benefits during the COVID-19 pandemic by reducing severe disease and mortality. On the other hand, the accelerated timeline for development and authorization meant that long-term effects could not be fully characterized at the time of deployment.

According to Resnik, responsible science requires that potential risks be proportionate to anticipated benefits and that uncertainties be transparently communicated. In emergency contexts, the ethical justification for rapid deployment rests on the magnitude and urgency of public health benefits. However, this justification also raises concerns regarding informed consent and public trust, particularly when scientific uncertainty is perceived to be minimized or inadequately explained.

4.2 Equity and Global Distribution

A second critical ethical concern involves equity in access to mRNA vaccines, which can be analyzed through Resnik's principle of justice. Ideally, the benefits and burdens of biomedical innovations should be distributed fairly across populations. In practice, early access to mRNA vaccines was largely concentrated in high-income countries, while many low- and middle-income countries experienced significant delays.

These disparities were shaped by systemic pressures, including intellectual property regimes, limited manufacturing capacity, supply chain constraints, and national prioritization of domestic populations. While such pressures reflect existing global economic and political structures rather than individual ethical failures, they nonetheless challenge the ethical ideal of equitable benefit sharing. The case of mRNA vaccines thus illustrates how technological success does not automatically translate into ethical outcomes when broader systemic factors are left unaddressed.

4.3 Dual-Use Concerns and Systemic Pressures

Although mRNA vaccine research is primarily oriented toward public health benefits, it also raises issues related to dual-use research of concern (DURC). The same platform characteristics that enable rapid vaccine development, such as modular design and scalable production, could be misused for harmful biological applications.

Managing DURC requires careful oversight, responsible communication, and institutional governance. However, these safeguards operate within a context shaped by systemic pressures, including urgency during public health crises, competition for funding, and incentives for rapid publication. Such pressures may complicate careful risk assessment and communication, increasing the importance of institutional responsibility in balancing openness with precaution.

Recommendations for Responsible Stewardship – Yuman Guo

Building on our ethical and societal analysis of mRNA vaccine technology, we recommend a set of concrete actions for researchers, institutions, industry, and policymakers to manage risks while maximizing public benefit. Our recommendations are guided by principles such as beneficence, justice, respect for persons, and social responsibility discussed in Resnik's framework, as well as lessons from COVID-19 vaccine roll-out and global inequities.

For researchers and developers

1. **Embed equity and diversity into research design.**
   Clinical trials for mRNA vaccines should intentionally recruit participants across age groups, sexes, racial and ethnic backgrounds, and comorbidities, including populations that have historically been under-represented in research. Transparent reporting of who is included—and who is not—helps prevent biased efficacy and safety data and aligns with principles of fairness and respect for persons.
2. **Strengthen long-term safety monitoring and data transparency.**
   Because mRNA platforms can be rapidly adapted for new pathogens, researchers should commit to robust post-marketing surveillance, data sharing, and independent re-analysis of safety signals. This includes registering trials, pre-specifying endpoints, publishing negative or inconclusive results, and sharing de-identified datasets when possible. Such practices promote accountability and help maintain public trust in a rapidly evolving technology.
3. **Practice careful, honest risk communication.**
   Scientists and company spokespeople should avoid overstating benefits or implying that mRNA vaccines are "risk-free" or "perfect." Instead, they should clearly communicate uncertainties, rare adverse events, and the comparative risks of infection versus vaccination. Using accessible language, visual aids, and culturally appropriate examples can make complex concepts—such as myocarditis risk or waning immunity—understandable to non-experts.
4. **Assess and mitigate dual-use risks.**
   While mRNA platforms are overwhelmingly used for beneficial purposes, they could in principle be misused to express harmful toxins or engineered viral proteins. Research groups should conduct dual-use risk assessments, follow DURC guidelines where relevant, and consult institutional biosafety and ethics committees when working with high-consequence pathogens or novel constructs. Not all experiments that are scientifically feasible are ethically justifiable.

For institutions, companies, and funders

1. **Establish governance structures for mRNA platform research.**
   Universities, research institutes, and companies should create or strengthen multidisciplinary oversight committees that include scientists, ethicists, legal scholars, and community representatives. These bodies can review high-impact mRNA projects, particularly those involving new delivery systems, self-amplifying RNA, or military and security applications, and can recommend safeguards or limits when societal risks outweigh benefits.
2. **Link public funding to access and affordability commitments.**
   Many mRNA vaccines were developed with substantial public investment. Funders and public agencies should attach conditions to grants and advance purchase agreements that require reasonable pricing, technology transfer, or participation in global mechanisms such as the WHO mRNA technology transfer hub. This aligns with the principle that publicly supported science should provide broad social benefit rather than only private profit.
3. **Invest in manufacturing capacity and knowledge sharing in low- and middle-income countries.**
   Institutions with advanced mRNA capabilities can partner with manufacturers in the Global South to provide training, process know-how, and quality-control support. Over time, distributed manufacturing can reduce dependence on a few high-income-country suppliers and make future pandemic responses more equitable and resilient.
4. **Promote an internal culture of ethics and reflection.**
   Companies and laboratories should integrate ethics discussions into routine activities—for example, lab meetings that briefly address societal implications, or annual workshops on research integrity and responsible innovation. Normalizing this type of reflection helps counteract systemic pressures such as speed, competition, and commercial secrecy.

For policymakers and public health authorities

1. **Strengthen regulatory capacity and pharmacovigilance systems.**
   Governments should invest in regulatory agencies so they can evaluate mRNA products efficiently while maintaining high safety standards. This includes training regulators in novel platform technologies, creating clear pathways for platform-based approvals, and building national systems that collect, analyze, and transparently report vaccine safety data.
2. **Advance fair global allocation in future crises.**
   To avoid repeating the extreme disparities seen during COVID-19, international bodies and national governments should negotiate advance agreements that tie early access to contributions to global pools, not only to purchasing power. Priority frameworks should explicitly protect health-care workers, high-risk populations, and countries with limited resources, reflecting ethical commitments to global justice rather than vaccine nationalism.

3. **Address misinformation and build trust through community partnership.** Public health communication about mRNA vaccines should be co-designed with local community leaders, health workers, and civil society organizations. Rather than only "debunking myths," authorities should listen to concerns, acknowledge historical abuses in medicine, and collaborate on messaging that respects local values. Investing in trusted messengers is more effective than relying solely on centralized campaigns.
4. **Protect privacy and prevent discriminatory uses of vaccination data.** If digital vaccine certificates or immunization databases are used, laws and regulations must limit data collection to what is necessary for public health and prohibit secondary uses such as employment or immigration screening that could fuel discrimination. Strong safeguards around data security and clear sunset clauses for emergency measures are essential.

Taken together, these recommendations aim to ensure that mRNA vaccine technology is governed in ways that are scientifically responsible, socially just, and worthy of public trust.

Conclusions and Team Reflection – Yuman Guo

mRNA vaccine technology represents a powerful and flexible platform that can rapidly respond to emerging infectious diseases and may soon be applied to cancer, rare genetic disorders, and other conditions. Our analysis shows that the same features that make mRNA vaccines transformative—speed, scalability, and modular design—also amplify ethical and social challenges. These include persistent inequities in access between and within countries, public mistrust fueled by misinformation and politicization, unresolved debates about intellectual property and profit in publicly funded science, and potential dual-use concerns. We conclude that the future of mRNA vaccines will depend not only on scientific innovation, but also on whether researchers, institutions, and policymakers are willing to prioritize transparency, global solidarity, and long-term safety over short-term advantage.

As a team, we learned that evaluating a technology like mRNA vaccines requires us to move beyond a simple "pro- or anti-vaccine" frame. We had to read across scientific, ethical, economic, and policy literatures, and we often realized that the same data could be interpreted differently depending on one's values and priorities. Discussing concepts from our course—such as Resnik's principles of responsible science, dual-use research of concern, and systemic pressures in research—helped us structure our thinking and ask better questions about who benefits, who is left out, and who bears the risks.

The collaborative process also taught us practical lessons about teamwork in STEM. Each member contributed different strengths: some focused on the molecular biology and clinical trial evidence, while others brought in perspectives on public health, global justice, and communication. Coordinating our writing, giving each other feedback, and merging sections into a single coherent report was sometimes challenging, but it mirrored real scientific collaboration, where clear communication and respect are as important as technical expertise. Overall, we came away with a deeper appreciation that responsible stewardship of mRNA technology is not

the task of a single expert or institution, but a shared responsibility of the entire scientific and global community.

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