

Research on the Mechanism of mRNA Vaccines in Overcoming Tumor Immune Escape

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Abstract: As a new approach to immunotherapy, mRNA vaccines have great potential in combating tumor immune escape. The article is a systematic literature review of both technical principles that form the basis of mRNA vaccines, main mechanisms of tumor immune escape, and the way they act in this regard. Initially, we present the key benefits of mRNA vaccines, such as fast production, strong immunogenicity, and positive safety data. Secondly, we discuss the major mechanisms of tumor immune escape, such as the inability to present antigens, the non-functional expression of immune checkpoint molecules, and the creation of an immunosuppressive microenvironment. We then consider the ways in which mRNA vaccines can counteract immune escape by improving antigen presentation, stimulating T cell response, T cell response, remodel the tumor microenvironment, and generate immune memory. With this groundwork, we discuss the molecular mechanisms whereby mRNA vaccines reduce immune escape, such as neoantigen targeting strategies, multifunctional T-cell induction, reversal of T-cell exhaustion, and combination of immune checkpoint inhibitors with synergistic effects. In addition, we conclude with the current clinical trial results and discuss the future perspectives and obstacles of mRNA vaccines in different types of tumors. This review develops a systematized model of the anti-tumor immune escape mechanism of mRNA vaccines with an integrated view of the underlying mechanisms of actions and theoretical underpinning of clinical application and further optimization.

Keywords: mRNA Vaccine; Tumor Immune Escape; Immunotherapy; Tumor Microenvironment; Immune Checkpoint Inhibitors.

1. Introduction

Cancer has been one of the biggest killers around the world. It is expected that in 2023, there will be 18.5 million new cases of cancer and 10.4 million deaths from cancer in the world. And between 1990 and 2023, overall cancer deaths have risen 74.3% [1]. Though the Conventional like surgery, chemotherapy & radiotherapy gave great results, they too much of toxicity like bone marrow suppression. And also it is a problem with these therapies due to drug resistance and recurrences as well as having little effect on those who have metastases or a resistant form of tumor.

In recent years tumor immunotherapy is a new therapy which makes use of the patients immune system to identify and destroy tumor cells. Tumor immune escape is a big problem for tumor immunotherapy. Tumor cells will use some complicated ways to avoid being found and killed by our immune system, so they can still live and grow when our body is trying to fight against them. Tumors may escape from the immune system using a lot of different ways; they might lessen the amount of tumor antigens so the immune system cannot spot them, increase molecules such as PD-1/PD-L1 which stop T-cells from working properly, change their surroundings called the tumor microenvironment (TME) to stop immune cells from coming in or doing anything, and make groups that can resist being attacked by the immune system through their different kinds and changes over time.

mRNA vaccines could be described as a new immunotherapy approach that is gaining increased attention in the field of tumor immunotherapy because of the unique benefits offered by mRNA in the context of antigen design, manufacturing, and safety. The lipid nanoparticle delivery system used in these vaccines allows the administration of mRNA with tumor-specific antigen (TSA) or tumor-

associated antigen (TAA) coding onto host cells where the target antigen can be expressed and the resulting T-cell immune response activated[2]. The effective development of the COVID-19 mRNA vaccine has confirmed the practicality of this platform, which has moved it much closer to clinical use in tumor therapy. There are currently many clinical studies on mRNA vaccine for tumors that demonstrate great promise in inducing particular T-cell responses and reducing the likelihood of reoccurrence of solid tumors, such as melanoma and pancreatic cancer[3].

Although there is a continuous growth in the amount of preclinical and clinical research data, the picture that exists today about the mechanisms behind mRNA vaccines is still incomplete. The majority of the studies have focused on individual elements, either antigen design or T cell activation, and have not developed a conceptual structure that explains the interactions between mRNA vaccines and the whole tumor immune cycle in a systematic way. Such absence of integration does not allow developing an overall picture of why mRNA vaccines can successfully revert diverse mechanisms of immune escape and produce synergistic interactions with other treatments including immune checkpoint inhibitors (ICI).

The purpose of this work is to build a systematic model of the concept of the mRNA vaccine anti-tumor immune escape mechanism by combining different pieces of evidence and explaining the underlying synergistic logic. The model attempts to offer a sound theoretical basis and testable hypotheses to the individualized design of vaccines and the optimization of combination therapy approaches, thus enabling the clinical use of these interventions.

2. Literature Review

2.1. Technical Principles and Core Advantages of mRNA Vaccines

The mRNA vaccine technology is rooted in studies on the concept of naked mRNA, which was made more stable upon modification of the nucleotides with one of the examples being pseudouridine and made more efficient in terms of delivery using the lipid nanoparticle (LNP) system. The effectiveness of the COVID-19 vaccine has hastened its use in the field of oncology. The vaccines by Pfizer/BioNTech and Moderna have established that their respective technology platforms are viable. In clinical trials, mRNA vaccines against antigens including HER2 have demonstrated potential in activating the immune system and suppressing the tumor in solid tumors, such as breast and pancreas cancers[4-6].

2.2. Key Mechanisms of Tumor Immune Escape

The most troublesome part in cancer treatment is that tumor immune escapes for many reasons. Tumor cells can affect antigen presentation by reducing their MHC molecules or mutating important antigens. In addition, the immune checkpoints such as PD-L1/PD-1 are also expressed abnormally and inhibit the T cells so that they do not work properly. Other cells also get called into the tumor microenvironment, regulatory T cells (Tregs), and myeloid-derived suppressor cells (MDSCs) also limit the anti-tumor immune response by releasing suppressive cytokines and through cell - cell interactions. Also due to heterogeneity of the tumor, different subpopulation would have different antigens and it leads to immune escape [7].

The complex nature of this immune evasion strategy makes traditional treatment options such as surgery, radiotherapy, chemotherapy, and immune checkpoint inhibitors effective in only a limited number of patients, and it also makes the maintenance of therapeutic responses difficult. Simultaneously, it helps to develop tumor progression, metastasis, and development of treatment resistance.

2.3. Current Research Gaps

Although the clinical trial outcomes of mRNA vaccines are encouraging, the mechanisms of action have not been studied as a whole, which results in rather disjointed studies. At the moment, there is a lack of a theoretical framework that explains how mRNA vaccines pass through various immune escape mechanisms one by one. Therefore, the creation of a multi-dimensional and dynamic model of how mRNA vaccines can escape anti-tumor mechanisms of immunity would not only explain the overall process of immune activation starting with the presentation of antigens and ending with the development of immune memory but provide the important theoretical backing of personalizing vaccine designs and informing combination therapies with immune checkpoint inhibitors.

3. Research Contents

3.1. Analysis of the Technical Principles and Core Advantages of mRNA Vaccines

The mRNA vaccines that use the mRNA technology cause the host cells to make a certain antigen after the messenger

RNA is transported into the cells, after which the cells start to produce the protein antigen. Compared to traditional vaccines, the new vaccine made by mRNA has.

3.1.1. The Ability to Develop and Produce Rapidly

The process of manufacturing mRNA vaccines is more efficient than the process of making conventional vaccines. After identifying the genetic sequence of the pathogen, vaccine designs and production can be done fast. Such an advantage offers a significant advantage when dealing with emerging infectious diseases such as the COVID-19 vaccine and the mResvia vaccine.

3.1.2. It has Strong Immunogenicity

The mRNA vaccines will be capable of evoking both humoral and cell based immune responses in particular that includes CD8 + T cell mediated immunity and that mostly takes place through Cytotoxicity it plays very important role in elimination of pathogen or tumor cell present inside the cell.

3.1.3. High Security

The mRNA vaccines are not live virus containing and hence can minimize the risk of viral infection in the body. Moreover, mRNA only stays in the cells during a short period of time, which makes it significantly less probable that the exposure will be long-term.

3.1.4. It has the Advantage of Personalized Design

The mRNA vaccine technology enables developing and manufacturing vaccines in quick time; different types of vaccines can be quickly created to meet the needs of each patient, especially the ones targeting tumor antigens which are tumor specific antigens.

mRNA vaccine concept in tumor immunotherapy, that is, the patient's immune system is stimulated to identify and eliminate tumor cells by means of mRNA coding of TSA or TAA. In order to create the mRNA vaccines the molecular structure is carefully created to include a 5-capped structure, a 5' and 3'- untranslated region (UTR) as well as an open reading frame and a 3'-polyadenylate tail. All contribute to the stability and efficiency of translation and longevity of the mRNA. As for the delivery system, LNP, which stands for Lipid nanoparticles, have become the main carriers consisting of ionizable lipids, helper lipids, cholesterol, and PEG-lipids. It's also important to consider that these ionizable lipids are positively charged at low pH, which helps to package the mRNA, are mostly neutral at physiological pH to decrease toxicity and increase the release of mRNA out of the endosome into the cytosol.

3.2. Analysis of the Key Mechanisms of Tumor Immune Escape

Tumor immune escape refers to the tumor cell's ability to evade being identified and destroyed by the immune system of the host. This is a major part of tumor growth and spreading. Immune-editing hypothesis is divided into three steps: clearance step, persistence step and escape step. The TME formed an immunosuppression environment in the escape stage which infiltrated with immunosuppressive cells and malfunctioned effector T cells. Main ways of immune avoidance:

3.2.1. Defect in Antigen Presentation

The tumor cells will reduce the expression of MHC molecule, or it will mutate the important antigen, so that the tumor cells can not be recognized by the T cell. Especially, the tumor cells may utilize some gene mutation or epigenetic change to disable MHC-I molecules, transporters concerning

with the material processing process (TAP1/2), and also the gene of β 2-microglobulin. And the effect of this operation is to disable the cell-based version of an antigen display cabinet, so that immune cells are unable to identify intracellular aberrations.

3.2.2. Abnormal Expression of Immune Checkpoint Molecules

The tumor cells have more immune checkpoint ligands such as PD-L1 which binds to the PD-1 on the surface of the T-cells and eventually causes the T-cells to become functionally exhausted. PD-1 and PD-L1 interact, the intracellular signaling pathways in T cells are changed, their ability to grow, be cytotoxic, and sometimes die is less.

3.2.3. Immunosuppressive Microenvironment

The Accumulation of Immunosuppressive Cells, such as T regulatory (Treg) cells and myeloid-derived suppressor cells (MDSCs), in the tumor microenvironment results in the inhibition of effector T cells via secretion of inhibitory cytokines, like IL-10 and TGF- β , or by direct intercellular contact. Treg cells are important in diminishing immune responses. MDSCs interfere with T cell metabolism and functionality by reducing important amino acids, including arginine, and by generating reactive oxygen species.

3.2.4. Metabolic Competition

The fast spread of tumor cells is accompanied by high utilization of important nutrients, such as glucose, in the microenvironment. Such depletion causes infiltrating T cells to undergo a "starvation" state, which disrupts their typical operation because they do not have enough energy.

3.2.5. Tumor Heterogeneity

The tumor cells are highly heterogeneous. Subpopulations may be expressing different antigens so that certain clones can escape attacks by the immune system on particular antigens.

Both of these mechanisms are coordinated to allow tumor cells to survive and replicate in the presence of the immune surveillance of the host, and this is why the efficacy of immunotherapy is also limited.

3.3. Integration of the Pathways and Mechanisms of mRNA Vaccines in Overcoming Immune Escape

The mRNA vaccines are able to counteract tumor immune escape in several ways. The most important mechanisms of action are:

3.3.1. Enhance Antigen Presentation

The tumor antigens made by mRNA vaccines can also be well taken in and shown by APCs causing both CD8+ and CD4+ T cells to respond to MHC class I and II molecules. DCs get targeted more directly by these vaccines, and they cause a better performance at presenting antigens by DCs using the chemokines CCL19 and CCL21. LNP delivery system protects mRNA from degradation and is endocytosed by DCs. After entering the cell, mRNA exits the endosome and enters the cytoplasm where it is translated into the protein antigen. And then get chopped up by proteasome and then load on to MHC Class I (cross-presented) or load onto MHC Class II via lysosomal pathway, so you get a response from CD8+ and CD4+ all at once.

3.3.2. Activate T-cell Responses

Induction of mRNA vaccines causes antigen presentation that leads to Tumor-specific CD8+ and CD4+ T cells, which produces Cytotoxic T lymphocytes to kill the tumor cell

directly. CD8+ T cells, which are also known as killer T cells, causes the death of cancer cells by apoptosis through the release of perforin and granzyme. On the other hand, CD4+ T cells, in particular, Th1 cells are helper cells for CD8+ T cells, which assist in the proliferation and active survival of CD8+ T cells through the release of IL-2 and IFN- γ . Also it can produce memory T cells like central memory T cell(TCM) and effector memory T cell(TEM) to provide us with the protection for a long time.

3.3.3. Reshaping the Tumor Microenvironment

mRNA vaccines might also decrease the amount of immunosuppressive cells like T-regulatory cells (Tregs), myeloid-derived suppressor cells (MDSCs) and so on in the tumor environment. It can help with the entry of effector T cells, turning an immunosuppressive tumor microenvironment into an immunosupportive tumor microenvironment. It is based on tumor specific T cells induced by the vaccine producing Interferon- γ (IFN- γ). This cytokine increases ISG expression by JAK1/JAK2-STAT1. This in turn leads to increased expression of major histocompatibility complex (MHC) class I molecules on tumor cells and changes in the cellular composition and functional state of the tumor microenvironment in order to facilitate the recruitment of further effector cells, as well as preventing the recruitment and activity of Treg and MDSCs.

3.3.4. Induce Immune Memory

mRNA vaccines are capable of inducing long-term immune memory, which includes the formation of central memory T cells and effector memory T cells that provide long-term immunity against tumors. Moreover, the nucleoside modification of mRNA vaccines can also impact on the development of immune memory. Compared to unmodified mRNA, nucleoside-modified mRNA might have differences in their ability to produce long-lasting immune memory[8].

3.3.5. Overcoming MHC Down-regulation

The interferon- γ (IFN- γ) produced by tumor-specific CD8+ T cells that are elicited by vaccines may have a paracrine impact on neighboring tumor cells, which would result in the reactivation of the expression of MHC class I molecules. In this process, the capability of antigen presentation is restored and inaccessible tumor cells are now exposed to the immune system surveillance once again.

3.4. Integration and Validation of combined treatment Strategies in Mechanism Models

The combined approach of treatment with mRNA vaccines and immune checkpoint inhibitors is a promising direction of contemporary tumor immunotherapy. The main synergistic mechanisms of combined therapy are:

3.4.1. Enhance Antigen Presentation and T Cell Activation

mRNA vaccines code tumor-specific antigens, such as tumor-specific antigens (TSA) and tumor-associated antigens (TAA). They are able to bind and activate dendritic cells (DCs) in lymph nodes, with the ability to cause an increase in CD8+ and CD4+ T cells through cross-presentation of MHC class I and II molecules. Not only does this mechanism greatly diversify the tumor-specific T cell libraries, but it also provides extra "releasable" effector targets to be used by the following step of immune checkpoint inhibitors (ICIs).

3.4.2. Release Inhibition and Enhance Killing

In the tumor microenvironment (TME) tumor cells try to evade immune watch because they have a lot of immune

checkpoints on them like PD-1. Inhibiting these signals is also possible with the use of immune checkpoint inhibitors (ICIs), for example, anti-PD-1 and anti-PD-L1 antibodies, which will be able to restore the effector function of T cells. And at the same time, the increased T-cell infiltration of the augmented T-cell infiltration of the augmented T-cells that are caused by the mRNAs contributes to the more specific and more effective ICIs. So this combination is going to allow for a much more effective and accurate removal of local tumor cells.

3.4.3. Immune Microenvironment Remodeling

The mRNA vaccine is stimulated, the expression of chemokines such as CXCL9, CXCL10 is increased by the type 1 interferon pathway, and effector T cells enter the tumor microenvironment (TME). Meanwhile, ICIs also remove the repressive characteristics of Treg cells by switching on the CD8+ T cells and increasing the number of effector T cells to Treg cells. And also, ICIs periodically make inhibitory cells, such as myeloid-derived suppressor cells (MDSCs), less active, which makes the TME less inhibitory. Both these together, it changes the state of the TME to an immunosuppressive.

3.4.4. Coordinate to Maintain Long-term Protection

Not only do mRNA vaccines help in proliferation of effector T cells during the T cell activation stage but also, and most importantly, these help in generation of central memory T cells (TCM) and effector memory T cells (TEM). The process forms a cell base for a long time of protection. Icos inhibitors (ICIs) prevent this activated form of T cell, thus the formation of memory T cells are not exhausted or clonally deleted once the antigen is cleared. And this increases the function life and survival. This induction-maintenance is finally giving patients more enduring anti-tumor immune surveillance which can reduce the chance of tumor recurrence and bring about long-term clinical benefit.

3.5. Clinical Translation Interface Analysis of mRNA Vaccines

3.5.1. Clinical Application Prospects

The possibilities and constraints of applying mRNA vaccines to different forms of tumors are as follows according to available clinical trial information: (1) Melanoma: High-risk melanoma treatment using both mRNA vaccines and pembrolizumab is associated with a significant decrease in the likelihood of recurrence or death, suggesting that it may be well clinically applied. BNT111 has also demonstrated a positive objective response rate in individuals with anti-PD-1 refractory melanoma, and hence presents a novel therapy alternative to those who are resistant to immunotherapy[6]. (2) Pancreatic Cancer: Individualized mRNA vaccines, like cevumeran/BNT122, have generated considerable neoantigen-specific T-cell reactions of patients with pancreatic ductal adenocarcinoma (PDAC), which are associated with longer recurrence-free survival (RFS), and offer new therapeutic prospects to this type of cancer with a bad prognosis[9]. (3) Breast Cancer: The ability of mRNA vaccines against tumor-associated antigens, like HER2, to induce an immune response and suppress tumors in clinical trials has been shown to provide new opportunities in the field of immunotherapy to treat breast cancer[5].

3.5.2. Challenges Faced

Clinical implementation of mRNA vaccines has a number of problems: 1. Efficiency of delivery: There is also a need to

enhance the efficiency of mRNA vaccine delivery especially with regards to delivering them to dendritic cells in tumors and lymph nodes. Future research needs to aim at lipid nanoparticles (LNPs) that will target dendritic cell surface receptors like those with mannose and self-amplifying mRNA (saRNA) technology to decrease dose and prolong expression time. 2. Suppression of tumor microenvironment: Although mRNA vaccines have the ability to change the tumor microenvironment, their effectiveness is limited in highly immunosuppressed environments. Some patients may have a total absence of MHC class I molecules on tumor cells or a mutation of the beta 2-microglobulin gene, preventing the infiltration of T cells into tumor cells. 3. Mechanisms of immune escape: Cancer cells are able to develop by undergoing a process of antigen loss or lineage transition that leads to new clones with no original antigen and able to escape the immune response. Multi-epitope vaccine design could be a possible approach to counter this problem. 4. Safety: Although mRNA vaccines have been associated with good safety profile, long-term safety should be considered, especially regarding the risks of autoimmune reactions and cytokine storms. 5. Production cycle: The existing production cycle of personalized neoantigen vaccines, which takes about 4-6 weeks, might take too much time to treat patients with fast-growing diseases, and thus, the production cycle needs to be optimized further.

3.5.3. Future Research Directions

The directions in which future research studies should be taken to maximize the clinical use of mRNA vaccines are: 1. Better delivery systems: The work towards the creation of more effective and safe delivery systems should be done to ensure the stability and efficiency of mRNA vaccine delivery especially by using active delivery technologies that deliver to the specific immune cells. 2. Customized vaccine design: The prediction of high-affinity neoantigens may be made using the patient's tumor-specific antigen profile by applying whole exome sequencing and bioinformatics algorithms (including pVAC-seq and NetMHCpan) to develop a customized mRNA vaccine that enhances the targeting and efficacy. 3. Combination treatment approach: The comprehensive investigation of the integrated use of mRNA vaccines with other forms of immunotherapy (including immune checkpoint inhibitors and cell therapy) or conventional therapies (including chemotherapy and radiotherapy) should be conducted along with the creation of the best timing and combination schedules depending on the comprehension of the underlying processes. 4. Biopromoter generation: To select patients and monitor their efficacy, developing biomarkers to forecast the success of mRNA vaccines is vital to enable accurate immunotherapy.

4. Conclusion

The development of mRNA vaccines as an immunotherapy approach has demonstrated great potential in tackling tumor immune escape. The vaccines are capable of triggering anti-tumor immunity by increasing the process of antigen presentation, inducing T cell responses, recasting the tumor microenvironment, and creating immune memory. On the molecular scale, mRNA vaccines are aimed at tumor neoantigens, bypass central tolerance and initiate high-affinity T cell libraries. They promote the generation of long-term immune memory by generating responses in multifunctional CD4+ and CD8+ T cells, which remodel the

tumor microenvironment via the IFN- γ signaling pathway and thus reverse the immunosuppressive state. It is important to note that the association between mRNA vaccine and immune checkpoint inhibitors has proven extremely synergistically anti-tumor effects in clinical studies. The synergy can be explained by the fact that vaccines increase tumor-specific T cell infiltration whereas checkpoint inhibitors counteract the inhibitory signals that act on these T cells.

The present-day studies still face the same issues, such as the efficiency of delivery, inhibition of the tumor microenvironment, and immune escape mechanisms. But, due to the continuous improvement of technologies and the accumulation of clinical experience, mRNA vaccines are expected to become an important therapy in the treatment of tumors in the future. Also, the mechanisms of drug resistance found in some patients, like the total absence of MHC Class I molecules and alterations in the patterns of antigen loss, point

to opportunities to improve.

Future studies should focus on: The first is improving on mRNA vaccine design and delivery systems for better stability and targeting. Second, the use of mRNA vaccines with other treatments such as immune checkpoint inhibitors. Lastly, we need more clinical trials so as to prove the efficiency and safety of mRNA vaccines when applied in different kinds of tumor, and bring some new information and ways to tumor immunotherapy.

To sum up all these kinds of researching information to be something like what we call mRNA vaccine anti-tumor Immune escape framework(Figure 1), so it's easier for us to have an insight in improving design for mRNA vaccine, providing some suggestions for combined therapeutic methods as well as predict better clinical outcome. At last give more precise and effective tumor immunotherapy method.

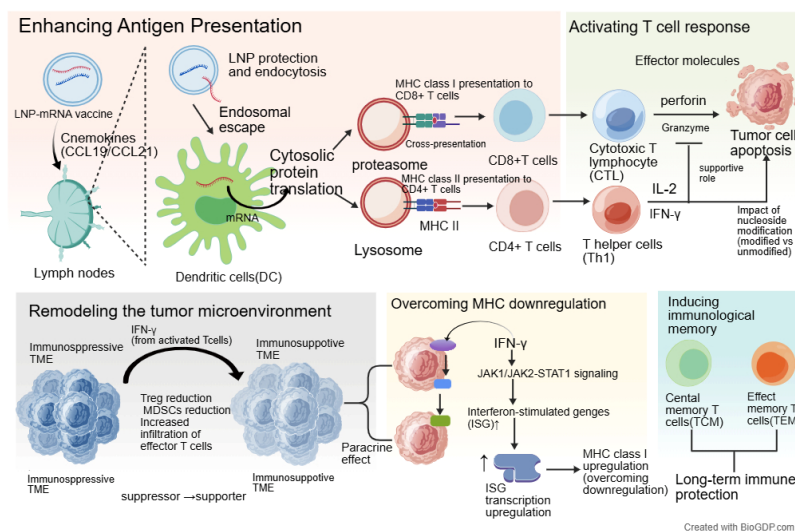


Figure 1. Mechanisms of mRNA Vaccines in Anti-Tumor Immune Evasion [10]

References

- [1] GBD 2023 Cancer Collaborators, Force, L. M., Abbas, N., Nekouei, O., Jin, W., Vos, T., & Murray, C. J. L. (2025). The global, regional, and national burden of cancer, 1990–2023, with forecasts to 2050: A systematic analysis for the Global Burden of Disease Study 2023. *The Lancet*, 406(10512), 1565–1586. [https://doi.org/10.1016/S0140-6736\(25\)01521-7](https://doi.org/10.1016/S0140-6736(25)01521-7).
- [2] Lv, Z., & Dai, Y. (2025). mRNA vaccines and siRNAs targeting cancer immunotherapy: Challenges and opportunities. *Discover Oncology*, 16(1), 1265. <https://doi.org/10.1007/s12622-025-02138-5>.
- [3] Lorentzen, C. L., Haanen, J. B., Met, Ö., & Svane, I. M. (2022). Clinical advances and ongoing trials on mRNA vaccines for cancer treatment. *The Lancet Oncology*, 23(10), e450–e458. [https://doi.org/10.1016/S1470-2045\(22\)00464-2](https://doi.org/10.1016/S1470-2045(22)00464-2).
- [4] Wang, X. J., Wang, W., & Shen, B. Y. (2025). mRNA vaccines: A new dawn for personalized treatment of pancreatic cancer. *Journal of Clinical Hepatology and Biliary Diseases*, 41(4), 619–624.
- [5] Li, J. Y., Jiang, R. Y., Wang, J., & Wang, X. J. (2025). Advances in mRNA vaccine therapy for breast cancer research. *Discover Oncology*, 16(1), 673. <https://doi.org/10.1007/s12622-025-01896-6>.
- [6] Thirupathi, J., Vijayan, V., Hwang, H. S., Bang, Y. J., Loeurng, V., Hong, S. H., Sundaram, A., Park, I. K., Lee, S. E., & Rhee, J. H. (2025). Thermoresistant flagellin-adjuvanted cancer vaccine combined with photothermal therapy synergizes with anti-PD-1 treatment. *Journal for Immunotherapy of Cancer*, 13(3), e010272. <https://doi.org/10.1136/jitc-2024-010272>.
- [7] Tufail, M., Jiang, C. H., & Li, N. (2025). Immune evasion in cancer: Mechanisms and cutting-edge therapeutic approaches. *Signal Transduction and Targeted Therapy*, 10(1), 227. <https://doi.org/10.1038/s41392-025-02278-6>.
- [8] Wei, Y. Z., Gong, X. H., Fan, C. Y., Zhang, Y. Q., Wang, S. S., & Du, F. (2025). mRNA vaccines and immune memory: Mechanisms, challenges and prospects. *China Journal of Medical Sciences*, 39(1), 77–81.
- [9] Bloom, M., Shaikh, A. R., Sun, Z., Bashir, B., & Snook, A. E. (2025). Cancer vaccination and immune-based approaches in pancreatic cancer. *Cancers*, 17(14), 2356. <https://doi.org/10.3390/cancers17142356>.
- [10] Jiang, S., Li, H., Zhang, L., Mu, W., Zhang, Y., Chen, T., Wu, J., Tang, H., Zheng, S., Liu, Y., Wu, Y., Luo, X., Xie, Y., & Ren, J. (2025). Generic Diagramming Platform (GDP): A general database of high quality biomedical diagrams. *Nucleic Acids Research*, 53(D1), D1670–D1676. <https://doi.org/10.1093/nar/gkac866>.