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Drug Development of Antibiotics and Vaccines for Infectious Diseases

Zitong Zhao[1,a,*]

[1]*Liverpool University, Oxford Street, Liverpool City, British Country*
a. hlzzhao5@liverpool.ac.uk
**corresponding author*

Abstract: Infectious diseases are diseases with a high mortality rate. In recent years, researchers have been studying new treatments to treat infectious diseases. Infectious diseases include COVID-19 and HIV-1 caused by the SARS-CoV-2 virus. Some antibiotics and vaccines are very helpful in preventing them. Inactivated viruses, attenuated viruses, and self-amplifying mRNA vaccines have also improved the treatment level of vaccines. This study systematically analyzes the roles of antibiotics, vaccines, and emerging technologies in combating infectious diseases, with a focus on COVID-19 and HIV-1. It highlights how modern biotechnology, particularly mRNA platforms, has revolutionized vaccine development while addressing the challenges posed by AMR. Despite these advances, significant limitations remain. While self-amplifying mRNA vaccines hold great promise, challenges related to stability, delivery, and large-scale production hinder their widespread application. Future research should prioritize improving these technologies to overcome such barriers. Additionally, the exploration of molecular targeted therapies that specifically address the root causes of infection and mitigate resistance is essential to combat AMR effectively.

Keywords: Infectious diseases,vaccines, SARS-CoV-2, HIV-1, inactivated virus vaccines

1. Introduction

Infectious diseases are the majority of causes of illness and death in the world today. In recent years, antibiotics and vaccines have been created to improve health and reduce mortality and are used to treat patients with infectious diseases[1]. Chiș et al. pointed out that researchers developed antibiotics and put them into clinical use in the early 20th century[2]. At the same time, vaccines are also a way to eliminate harmful sources of infection and provide people with immunity for many years or a lifetime[1]. The interaction between microorganisms such as bacteria or fungi and host organisms can lead to the generation and spread of diseases [3]. Infectious diseases include COVID-19, caused by the SARS-CoV-2 virus and HIV-1. Breakthroughs in mRNA technology and analysis of viral spike proteins have promoted the rapid development of COVID-19 vaccines. In addition, researchers have overcome the high variability of HIV-1 by making HIV-1 vaccines by specifically recognizing and activating precursor B cells of broadly neutralizing antibodies (bnAbs). However, the development of antimicrobial resistance (AMR) makes antimicrobial drugs ineffective against the proliferation of microorganisms [2]. In this case, the therapeutic effect of infectious diseases will be reduced, and the mortality rate will increase significantly. In addition, inactivated virus vaccines,

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attenuated virus vaccines, and self-amplifying mRNA vaccines have also made great contributions to the prevention of infectious diseases and have been continuously updated and improved.

This study aims to systematically analyze the role of antibiotics, vaccines and other means in the treatment and prevention of infectious diseases, and explore the impact of antimicrobial resistance (AMR) and its response strategies. Through the study of typical infectious diseases such as COVID-19 and HIV-1, it reveals how modern biotechnology (such as mRNA technology) promotes vaccine development, and summarizes the contribution of traditional vaccines (such as inactivated vaccines and attenuated vaccines) in public health. The ultimate goal is to provide a theoretical basis and practical guidance for improving the treatment and prevention and control strategies of infectious diseases. This paper will systematically sort out the existing literature on the development, application and effects of antibiotics and vaccines through a literature review, and analyze the historical development, current challenges and future trends. This study will further deepen the understanding of antibiotics, vaccines and their core role in the prevention and control of infectious diseases, and provide theoretical support for understanding the contribution of emerging technologies (such as mRNA technology) in vaccine development. In addition, by analyzing the challenges of AMR, this study provides an important reference for drug development and public health policy formulation.

2. Overview of Vaccine development and social impact

Prevention measures for infectious diseases are mainly achieved through vaccines, which can increase the survival rate of patients, reduce the number of people infected with infectious diseases, and promote social progress and development[4]. Haynes pointed out that for most viral infectious diseases, vaccines containing neutralizing antibodies can induce immunity. Flu vaccines have been widely used since the mid-20th century and are updated annually to address the rapid mutation of the virus. They have effectively reduced infection rates, hospitalizations, and mortality, especially among vulnerable groups such as children, pregnant women, and the elderly. In addition to personal health benefits, widespread flu vaccination helps reduce the burden on healthcare systems during peak seasons. Similarly, the measles, mumps, and rubella (MMR) vaccine has played a key role in the near eradication of these diseases in many parts of the world. It has not only prevented millions of deaths, but also avoided serious complications such as encephalitis and hearing loss, and helped improve child survival and long-term quality of life. The development of COVID-19 vaccines in recent years, utilising cutting-edge technology like viral vector platforms and mRNA, has revolutionised the fight against diseases. These immunisations have been crucial in lowering mortality and serious illness, promoting social openness, and reviving international trade. Collectively, these instances demonstrate how vaccinations can foster advancements in medical research, public health facilities, and global collaboration in addition to lessening the effects of infectious diseases.

3. Analysis of the Current Status of Vaccine Technology and Application

3.1. Comparison Between SARS-CoV-2 and HIV-1 Vaccines

Vaccine development has made remarkable strides, but the challenges posed by different viruses highlight the complexity of creating effective solutions. SARS-CoV-2 and HIV-1 are both positive-strand RNA viruses. Researchers first discovered the coronavirus 2 (SARS-CoV-2) variant Omicron (B.1.1.529) at the end of 2021 [5]. However, when the host is infected with SARS-CoV-2, the virus can be cleared from the body, but individuals infected with HIV-1 cannot do so. SARS-CoV-2 mutates slowly and cannot integrate into the host's genes. Vaccine-induced secondary immunity can eliminate cells damaged by the virus. HIV-1 virus can integrate into the host genome to form a pool of CD4+T cells. The neutralizing antibody target for SARS-CoV-2 is the receptor binding domain (RBD) of the viral spike protein (S protein), and the neutralizing antibody target for HIV-1 is the viral

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envelope protein (Env). In comparison, HIV-1 poses even larger obstacles. The virus integrates into the host genome, creating a difficult-to-eliminate reservoir in CD4+ T cells. Vaccine development is further difficult by the requirement for broadly neutralising antibodies (bnAbs), which necessitate rare somatic mutations and large heavy chain complementarity determining regions. To overcome these challenges, researchers must analyse bnAb precursor B cells and create mutant intermediate B cells capable of activating antibody precursors, a difficult and resource-intensive process.

3.2. The Evolution and Methods of Influenza Vaccine Development

Influenza vaccinations began to be available around 1930, and inactivated influenza vaccines were allowed in 1945 [6][7][8][9]. Over the decades, inactivated viruses have been a cornerstone in vaccine development, offering a safer and simpler production process for protecting against viral pathogens. The production method involves culturing viruses on substrates such as primary cells or fertilized eggs to obtain antigens. Once propagated, the viruses are purified, concentrated, and inactivated using physical or chemical methods, including heat or ascorbic acid [10]. Inactivated vaccines, while advantageous in safety, often exhibit lower immunogenicity compared to other vaccine types, necessitating multiple doses or the use of adjuvants to achieve effective protection. This, in turn, increases production costs and complexity. After the virus is propagated, the pre-inactivated virus is purified and concentrated and then inactivated by physical or chemical methods, such as heat and ascorbic acid. Inactivated vaccines have lower immunogenicity than other vaccines, so multiple doses or adjuvants may be required, which increases the production cost and complexity of production to a certain extent. Formaldehyde, among aldehydes, is the main inactivating agent in vaccine production. Most pathogens are modified by formaldehyde under the condition of cross-linking of multiple amino acids, which causes changes in proteins and makes the virus lose its ability to infect. However, temperature, duration, and reagent concentration all affect the effectiveness of inactivated vaccines. Generally, the speed of inactivation of viruses is proportional to the formalin concentration and temperature. However, to ensure complete inactivation of the virus and protect immunogenicity, it is necessary to control the inactivation time moderately[6].

Beta-propiolactone (BPL) is another effective inactivating agent, often preferred for its potency over formaldehyde. The principle of using BPL to inactivate viruses and make inactivated vaccines is that BPL directly contacts nucleic acids to cause alkylation and acylation reactions[6][11][12][13]. The Nitrogen-7 atom of guanosine reacts with BPL, and the polymerase misrecognizes the BPL-modified guanine as an adenine, so a GC-AT transition mutation is added to each alkylated guanine [6][14][15]. BPL-induced DNA double helix cross-linking combined with multiple mutations impairs gene function, leading to difficulty in viral replication and loss of activity[6][16]. In addition, the immunogenicity of BPL will also change due to different pathogens. The effect of inactivating viruses is related to the type of virus, BPL concentration, temperature and so on.[6][17].

In parallel, live attenuated viruses (LAVs) have emerged as a highly effective strategy to vaccine production. These vaccines are made by culturing viruses in controlled cell culture settings and treating them to methods that purposely lower their virulence while maintaining their capacity to elicit a strong immune response [18]. By keeping the virus's ability to replicate, albeit in a weakened form, LAVs closely mirror natural infections, eliciting significant and long-lasting protection. This ability to elicit comprehensive immune responses frequently translates into effective protection against a wide range of infectious diseases, making LAVs an important tool in the fight against global health risks.

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3.3. Advancements and Challenges in Self-Amplifying mRNA Vaccines

Self-amplifying mRNA vaccines represent an advanced development in the field of vaccine technology, offering enhanced flexibility compared to traditional DNA vaccines while improving both immune responses and safety profiles [19]. Self-amplifying mRNA vaccines have greater therapeutic effects and development prospects than other vaccines in responding to large-scale infectious diseases [20]. Self-amplifying mRNA has more base pairs than non-amplified mRNA, including a cap, 5′ UTR, 3′ UTR, and poly(A) tail of variable length. The method to obtain this vaccine is to deliver nucleic acids to the cytoplasm, then amplify and produce corresponding antigenic proteins [19].Self-amplifying mRNA can enter the target cell, replicate itself, and then amplify in the body. When RNA comes into contact with the target cell, RNA needs to rely on the translocation of the cell membrane to reach the cytoplasm and translate specific proteins. Self-amplification can reduce the amount of vaccine used, provide equivalent immune effects, and reduce adverse reactions in patients.

Notwithstanding these benefits, a number of obstacles must be overcome before self-amplifying mRNA vaccines can be applied extensively. These difficulties include the inability to guarantee effective delivery of the nucleic acid to the cytoplasm, the intricacy of large-scale manufacturing, and the instability of mRNA in specific situations. Furthermore, using these vaccinations in people with weakened immune systems raises questions since their immune responses could not be as robust or consistent. These difficulties underscore the necessity of further investigation and refinement in the creation of self-amplifying mRNA vaccines.

4. Discussion

Vaccine research and development plays a vital role in reducing the impact of infectious diseases and promoting social progress. Successful cases represented by influenza vaccines, MMR vaccines, and Covid-19 vaccines have demonstrated the great value of vaccines in personal health and public health while promoting medical research progress and global cooperation. However, the complexity of different viral characteristics poses challenges to vaccine development, especially for viruses such as HIV-1, whose gene integration and the need for broad neutralizing antibodies make vaccine development extremely difficult.

In terms of technology, vaccines have evolved from traditional inactivated vaccines and live attenuated vaccines to new mRNA and self-amplifying mRNA vaccines, showing a leap in biotechnology. Traditional inactivated vaccines inactivate viruses by chemical or physical methods, but have low immunogenicity and complex production processes. Live attenuated vaccines provide stronger and more lasting immune responses by reducing the toxicity of the virus, but their safety and adaptability may be limited. In contrast, as an innovative technology, self-amplifying mRNA vaccines not only improve the immune effect, but also show obvious advantages in vaccine dosage and safety, but their instability, difficulty in large-scale production, and effectiveness of nucleic acid delivery still need further research and optimization.

In general, future drug development will prioritise improving the efficacy and targeting mechanisms of existing antibiotics and antiviral drugs, as well as discovering new molecular targeted drugs that address the root causes of infection more accurately. This method is crucial for lowering the possibility of medication resistance and limiting the formation of novel mutations that could impair the efficacy of current treatments. In vaccine development, the use of inactivated and attenuated virus technology will remain critical to enhancing vaccine immunogenicity and efficacy. These vaccines use attenuated or inactivated viruses to ensure that the human body recognises and responds to infections without producing disease. At the same time, self-amplifying mRNA

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technology has shown promising results in the creationof COVID-19 vaccines and is likely to play a significant role in increasing vaccine safety and effectiveness in the future.

5. Conclusion

This study emphasizes the indispensable roles of vaccines, antibiotics, and emerging technologies in combating infectious diseases, with a particular focus on SARS-CoV-2, HIV-1, and antimicrobial resistance (AMR). The rapid development and success of mRNA vaccines during the COVID-19 pandemic illustrate their transformative potential, revolutionizing the field of immunization by enabling faster production, enhanced efficacy, and reduced dosage requirements. Innovations such as self-amplifying mRNA technology further promise to improve vaccine safety, cost-effectiveness, and accessibility. These advancements have not only reshaped the global vaccine landscape but also revitalized HIV-1 vaccine research, which faces significant obstacles, including the virus's high mutation rates, immune evasion mechanisms, and the need for broadly neutralizing antibodies.

The growing threat of AMR—fueled by the overuse and misuse of antibiotics—underscores the urgent need for alternative therapeutic strategies. Novel approaches such as molecular targeted therapies and CRISPR-based antimicrobials offer promising solutions to counteract resistant pathogens, prevent further mutations, and address the limitations of traditional antibiotics.

However, despite these advances, significant limitations remain. While self-amplifying mRNA vaccines hold great promise, stability, delivery, and large-scale production-related issues remain barriers to their widespread use. Future research should focus on improving vaccine technology, especially self-amplifying mRNA platforms, to overcome current limitations related to delivery and stability. It is also critical to explore new molecular targeted therapies that specifically target the root of infection and mitigate the development of resistance.

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