REVIEW ARTICLE

Administration of Nanovaccines by Transdermal Drug Delivery System-current and Future Perspectives

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Abstract

Nanovaccines have emerged as a promising approach to enhance vaccination strategies, leveraging the power of nanotechnology to improve immune responses and vaccine efficacy. In recent years, the administration of nanovaccines through transdermal drug delivery systems has garnered significant attention. This review explores the research examples highlighting the utilization of transdermal drug delivery systems for nanovaccine administration. It discusses various nanovaccine delivery approaches, such as microneedle patches and lipid-based nanocarriers, and presents research studies demonstrating their efficacy and potential in immunization.

Key words: Immune response, lipid-based nanocarriers, nanovaccines, transdermal drug delivery

INTRODUCTION

Nanovaccines represent a revolutionary approach in the field of vaccination, leveraging the power of nanotechnology to enhance immune responses and improve vaccine efficacy. These vaccines are designed and engineered at the nanoscale, typically ranging from 1 to 100 nanometers in size, to optimize their performance.[1] By manipulating the composition, structure, and surface properties of nanovaccines, researchers can achieve precise control over antigen presentation, adjuvant delivery, and immune system activation.[2]

One of the key advantages of nanovaccines lies in their ability to mimic pathogen characteristics and enhance immune recognition. By incorporating antigens into nanoscale carriers, such as nanoparticles, liposomes, or virus-like particles, nanovaccines can more effectively engage immune cells and elicit robust immune responses.[3] The high surface-to-volume ratio of nanoparticles allows for efficient antigen loading, while the carrier itself can serve as an adjuvant, further enhancing the immune response. In addition, nanovaccines can be engineered to target specific immune cells or tissues, promoting tailored immune activation and enhancing vaccine efficacy.[4] Nanovaccines have shown significant potential in a wide range of infectious diseases, including viral infections such as influenza, human papillomavirus (HPV), and COVID-19, as well as bacterial infections like tuberculosis (TB). For example, in the context of COVID-19, nanovaccines based on lipid nanoparticles or viral vectors have demonstrated remarkable efficacy in preclinical and clinical studies, contributing to the rapid development of effective vaccines during the pandemic. Moreover, nanovaccines offer versatility and flexibility in their design, allowing for combination vaccines and multivalent formulations. Multiple antigens or adjuvants can be incorporated into a single nanovaccine, enabling

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Received: 18-03-2024
Revised: 27-05-2024
Accepted: 04-06-2024

simultaneous immunization against multiple diseases or strains. This approach can simplify vaccination schedules, improve compliance, and reduce the need for multiple injections.[5,6]

Nanovaccines and transdermal drug delivery systems

Nanovaccines and transdermal drug delivery systems are distinct concepts, but it is possible to combine them to create nanovaccine-based transdermal drug delivery systems [Figure 1]. In such systems, nanoparticles are used both as carriers for vaccines and as vehicles for transdermal drug delivery.[7]

The integration of nanovaccines into transdermal drug delivery systems offers several potential advantages:

- Co-delivery of vaccines and drugs: By incorporating both vaccines and therapeutic drugs into the same nanosystem, it is possible to achieve simultaneous vaccination and drug delivery. This can be particularly beneficial in certain disease conditions where both immune modulation and localized treatment are desired.[8]
- Enhanced immune response: Nanoparticles used in nanovaccines can help stimulate the immune system and improve the immune response at the site of application. When combined with transdermal drug delivery, these nanoparticles can elicit a targeted immune response while also delivering therapeutic drugs to specific tissues or cells.
- Improved stability and bioavailability: Nanoparticles used in transdermal drug delivery systems can protect both vaccines and drugs from degradation, ensuring their stability during storage and transportation. In addition, nanoparticles can enhance the bioavailability of drugs by improving their penetration through the skin barrier (Figure 2).
- Extended release profiles: Nanoparticles can be engineered to provide sustained release of vaccines and drugs, resulting in prolonged immune stimulation or therapeutic effects. This can reduce the frequency of administration and improve patient compliance.[9]

The development of nanovaccine-based transdermal drug delivery systems is an active area of research. Scientists are exploring various nanoparticle formulations, such as liposomes, polymeric nanoparticles, and inorganic nanoparticles, to create versatile systems capable of carrying both vaccines and drugs.[10] Overall, the integration of nanovaccines into transdermal drug delivery systems has the potential to revolutionize vaccination strategies and therapeutic interventions by combining the benefits of both approaches into a single system.[11]

Rationale for transdermal nanovaccine delivery

Transdermal nanovaccine delivery offers several advantages and rationale for its use.[12] Here are some key reasons for

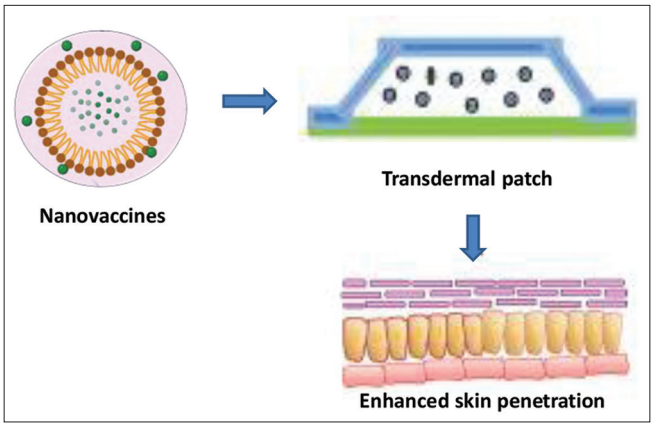

Figure 1: Administration of nanovaccines by transdermal drug delivery system

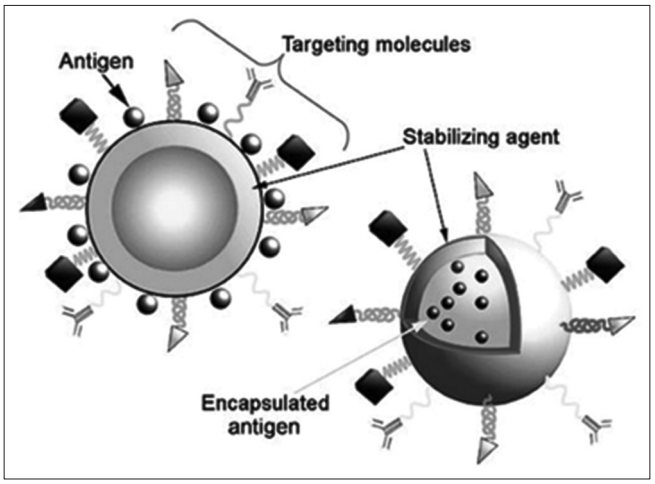

Figure 2: Nanovaccine

utilizing transdermal routes for nanovaccine delivery:

- Needle-free and painless administration: Transdermal delivery eliminates the need for injections, which can be uncomfortable and cause needle-related anxiety in some individuals. Nanovaccines administered through transdermal patches or other delivery systems provide a needle-free and painless alternative, which can improve patient acceptance and compliance.
- Enhanced patient convenience and self-administration: Transdermal nanovaccines can be designed for self-administration by patients, allowing for convenient and accessible vaccine delivery. This can be particularly beneficial in scenarios where health-care infrastructure is limited or in remote areas where access to medical facilities is challenging.
- Improved immune response at the site of action: Nanoparticles used in transdermal vaccine delivery systems can effectively target antigen-presenting cells in the skin, such as dendritic cells, which are crucial for initiating immune responses. By directly targeting these cells, transdermal nanovaccines can enhance the immune response at the site of administration.[13]
- Stimulation of skin-associated immune system: The

skin is rich in immune cells and serves as the first line of defense against pathogens. Transdermal delivery of nanovaccines can activate the skin-associated immune system, leading to a robust local immune response. This can be advantageous for diseases that primarily target mucosal surfaces or pathogens that enter the body through the skin.

- Potential for sustained release and controlled dosing: Nanoparticles used in transdermal delivery systems can be designed to provide sustained release of vaccine antigens. This controlled dosing allows for a more prolonged exposure to the immune system, leading to a sustained immune response and potentially reducing the need for multiple vaccine administrations.
- Enhanced stability and protection: Nanoparticles can protect vaccine antigens from degradation, improving their stability during storage and transportation. This is particularly beneficial for certain types of vaccines, such as those based on fragile or labile antigens, which may require specific temperature control or protection from enzymatic degradation.
- Improved vaccine delivery to targeted populations: Transdermal nanovaccine delivery may offer benefits for certain populations, such as individuals with needle phobia, pediatric patients, or individuals with compromised immune systems. It can provide a safer and less invasive option for vaccine administration in these cases.[14-16]

MICRONEEDLE PATCHES FOR TRANSDERMAL NANOVACCINE DELIVERY

Microneedle patch technology

Microneedle patch technology involves the use of tiny needles, typically ranging from tens to hundreds of micrometers in length, to create microneedles on a patch or substrate. These microneedles can penetrate the outermost layer of the skin, known as the stratum corneum, to deliver drugs, vaccines, or other substances into the skin in a minimally invasive and painless manner.[16,17]

Applications of microneedle patches:

a. Vaccine delivery: Microneedle patches have shown promise for delivering vaccines, including those against influenza, measles, polio, and COVID-19. They can target immune cells in the skin, leading to robust immune responses.
b. Transdermal drug delivery: Microneedle patches can deliver various medications, including pain relievers, hormones, anti-inflammatory drugs, and local anesthetics, through the skin.
c. Diagnostic applications: Microneedles can also be used for minimally invasive sampling of interstitial fluid or blood for diagnostic purposes, such as monitoring glucose levels in individuals with diabetes.[18,19]

Transdermal delivery of influenza nanovaccine

Research studies on the transdermal delivery of influenza nanovaccines have gained interest due to the potential advantages they offer. Influenza nanovaccines delivered through the skin offer several potential advantages:

- Enhanced immune response: Transdermal delivery of nanovaccines can stimulate the immune system in the skin, which contains a dense population of immune cells. This targeted delivery to the skin can potentially lead to a more robust immune response compared to traditional injection-based vaccination methods.
- Improved patient compliance: Transdermal delivery provides a needle-free and painless alternative to injections, which can improve patient acceptance, particularly in individuals with needle phobia or children. This may lead to higher vaccination rates and improved public health outcomes.[20]
- Simplified administration: Transdermal delivery of influenza nanovaccines can be designed for self-administration, reducing the need for health-care professionals and enabling individuals to conveniently apply the vaccine patches at home. This can be particularly beneficial in situations where access to health-care facilities is limited.
- Enhanced stability and storage: Nanovaccine formulations can be engineered to enhance stability, increasing shelf life and reducing the need for cold chain storage, which is especially advantageous for influenza vaccines in resource-limited settings.
- Potential for dose-sparing: Efficient transdermal delivery of nanovaccines may allow for lower antigen doses while still achieving protective immune responses. This could help address vaccine production and distribution challenges during influenza outbreaks or pandemics.[21,22]

COVID-19 nanovaccine delivery through microneedle patches

Transdermal delivery of COVID-19 nanovaccines through microneedle patches represents an innovative and promising approach for vaccination against the SARS-CoV-2 virus. This delivery method offers several advantages, including needle-free and painless administration, enhanced immune responses through targeted delivery to immune-rich skin layers, and the potential for self-administration, improving convenience and patient compliance. Furthermore, the integration of stable nanoparticles within microneedle patches ensures vaccine stability during storage and transportation, potentially alleviating cold chain requirements. The localized delivery to immune cells in the skin offers the possibility of dose-sparing and efficient antigen presentation, while ongoing research and clinical trials will be

crucial for assessing the safety, immunogenicity, and efficacy of COVID-19 nanovaccine delivery through microneedle patches. This approach holds promise for contributing to global vaccination efforts against COVID-19, and continued advancements in nanovaccine formulations and microneedle designs will be instrumental in realizing its full potential.[23]

Challenges of microneedle patch-based nanovaccines

i. Formulation and antigen stability: Formulating vaccines in nanoscale carriers for microneedle patches can be challenging. Ensuring vaccine stability, maintaining antigen integrity, and optimizing release kinetics are critical factors that require careful consideration.
ii. Skin barrier penetration: Efficient penetration of the skin barrier is crucial for effective vaccine delivery. Overcoming the skin's natural protective barrier and achieving sufficient delivery to immune-rich skin layers are areas that require further research and optimization.[24]
iii. Manufacturing complexity: Manufacturing microneedle patches with consistent quality, precise dimensions, and suitable materials can be technically demanding and may require specialized equipment and processes.
iv. Regulatory considerations: Microneedle patches fall under regulatory oversight, and obtaining regulatory approvals necessitates demonstrating safety, efficacy, and quality assurance of the nanovaccine delivery system.[25]

LIPID-BASED NANOCARRIERS FOR TRANSDERMAL NANOVACCINE DELIVERY

Lipid-based nanocarriers have emerged as promising tools for transdermal nanovaccine delivery. These nanocarriers, composed of lipid-based materials such as liposomes, solid lipid nanoparticles (SLNs), and nanoemulsions, offer several advantages in the field of transdermal vaccine delivery. Second, the composition and surface properties of lipid-based nanocarriers can be tailored to enhance their interactions with the skin and facilitate vaccine penetration. By modulating the lipid composition, size, and surface charge of the nanocarriers, their ability to cross the skin barrier and target antigen-presenting cells can be optimized, leading to enhanced immune responses.[26]

Furthermore, lipid-based nanocarriers can provide controlled and sustained release of vaccine antigens, ensuring a prolonged exposure to the immune system. This sustained release profile can promote a gradual and persistent immune activation, leading to improved immune memory and long-lasting protection. Lipid-based nanocarriers also offer versatility in terms of vaccine formulation and administration. They can be easily functionalized with targeting ligands, adjuvants, or other immune-modulating agents, enabling tailored and personalized vaccine delivery strategies. In addition, their non-invasive and patient-friendly transdermal route of administration eliminates the need for needles, improving patient compliance and reducing the risk of needle-related complications.[27,28]

Transdermal delivery of HPV nanovaccine using lipid-based nanocarriers

Transdermal delivery of HPV nanovaccines utilizing lipid-based nanocarriers holds significant potential for enhancing vaccination strategies against HPV infections. Lipid-based nanocarriers, such as liposomes and SLNs, offer advantages in terms of antigen stability, controlled release, and immune response modulation.[29]

Lipid-based nanocarriers can efficiently encapsulate HPV antigens, protecting them from degradation and preserving their immunogenicity during storage and transportation. The lipid bilayers of liposomes or the solid lipid matrix of SLNs can provide a protective environment for antigens, ensuring their integrity until reaching target cells in the skin. These nanocarriers can be designed to enable sustained release of HPV antigens, allowing for a prolonged exposure to the immune system. This sustained release profile enhances the duration and strength of the immune response, potentially leading to long-lasting protective immunity against HPV.[30]

Transdermal delivery of HPV nanovaccines using lipid-based nanocarriers provides a non-invasive and patient-friendly vaccination method, eliminating the need for traditional injections. This approach offers improved patient compliance and reduces the risk of needle-associated complications, particularly in the context of HPV vaccination programs targeting adolescents.[31]

Hepatitis B nanovaccine delivery through lipid-based nanocarriers

The delivery of hepatitis B nanovaccines using lipid-based nanocarriers represents a promising approach for effective vaccination against hepatitis B virus (HBV). Lipid-based nanocarriers, such as liposomes and SLNs, offer distinct advantages in terms of antigen protection, controlled release, and immunogenicity enhancement.

Lipid-based nanocarriers can efficiently encapsulate hepatitis B antigens, safeguarding them from degradation and preserving their immunogenicity during storage and transport. The lipid bilayers of liposomes or the solid lipid matrix of SLNs provides a protective environment that ensures the stability and integrity of the antigens until reaching the target cells in the skin. These nanocarriers can be engineered to facilitate controlled release of hepatitis B antigens, allowing for sustained exposure to the immune system. This sustained release profile promotes a prolonged and robust immune

response, potentially leading to long-lasting protection against HBV infection.[32] Transdermal delivery of hepatitis B nanovaccines using lipid-based nanocarriers provides a non-invasive and patient-friendly vaccination approach, eliminating the need for traditional injections.

OTHER TRANSDERMAL NANOVACCINE DELIVERY APPROACHES

Dendrimers and nanogels for transdermal nanovaccine delivery

Dendrimers and nanogels have emerged as promising nanocarrier platforms for transdermal nanovaccine delivery, offering unique advantages in terms of their structure, versatility, and immune modulation capabilities.

Dendrimers, highly branched and symmetric macromolecules, can be precisely engineered to carry vaccine antigens and adjuvants. Their well-defined structure allows for precise control over size, shape, and surface properties, enabling enhanced antigen loading and controlled release. Dendrimers can facilitate efficient antigen uptake by antigen-presenting cells in the skin, leading to robust immune responses. Furthermore, their surface can be functionalized with targeting ligands or immune-stimulatory molecules to achieve specific delivery and immune modulation.[33]

Nanogels, three-dimensional hydrogel nanoparticles, provide an ideal platform for antigen encapsulation and sustained release. Their porous structure allows for high antigen loading capacity, protecting antigens from degradation and providing sustained release kinetics. Nanogels can be formulated with biodegradable and biocompatible materials, enabling their efficient penetration into the skin and interaction with immune cells. In addition, their tunable properties, such as particle size and crosslinking density, allow for tailored release profiles and immune response modulation.[34]

Transdermal delivery of TB nanovaccine using nanogels

Transdermal delivery of TB nanovaccines using nanogels represents a promising approach for combating TB infections. Nanogels, three-dimensional hydrogel nanoparticles, offer several advantages for efficient vaccine delivery and immune response modulation.

Nanogels can effectively encapsulate TB vaccine antigens, protecting them from degradation and preserving their immunogenicity during storage and transportation. Their porous structure allows for high antigen loading capacity, ensuring efficient delivery of a sufficient amount of antigens to the immune cells in the skin. Moreover, nanogels can provide sustained release of antigens, enabling a prolonged exposure to the immune system and promoting a robust and durable immune response against TB [Figure 3].

The tunable properties of nanogels, such as particle size and crosslinking density, allow for precise control over the release kinetics and immune modulation. By tailoring these parameters, the release profile of TB antigens can be optimized to enhance the desired immune response, leading to improved vaccine efficacy.[35]

Nanovaccine delivery through dendrimers for malaria immunization

Nanovaccine delivery through dendrimers offers a promising approach for malaria immunization. Dendrimers, highly branched and symmetrical macromolecules, provide a versatile platform for the efficient delivery of malaria vaccine antigens and adjuvants.

One of the key advantages of dendrimers is their ability to enhance immune response modulation. They can promote the desired immune profile, such as the induction of strong T-cell responses or the generation of long-lasting memory immune cells, which are crucial for effective malaria immunization. Dendrimers can also provide sustained antigen release, leading to a prolonged immune response and potentially reducing the need for multiple vaccine doses.[36]

IMMUNOLOGICAL CONSIDERATIONS AND EFFICACY ASSESSMENTS

Immune responses induced by transdermal nanovaccines

Transdermal nanovaccines have shown the potential to induce robust and targeted immune responses. These nanovaccines, when delivered through the skin, interact with immune cells and tissues, leading to specific immune activation and enhanced vaccine efficacy.[37]

The adaptive immune response is also initiated by transdermal nanovaccines. Antigens delivered through the skin are taken

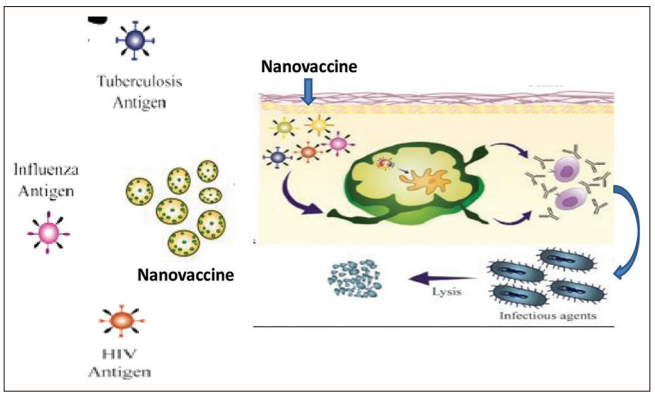

Figure 3: Prophylactic effect of nanovaccine delivery

up by antigen-presenting cells, which migrate to the draining lymph nodes. There, they present the antigens to T cells, initiating antigen-specific T cell responses. Transdermal nanovaccines can promote the activation of cytotoxic CD8+T cells, which play a crucial role in eliminating intracellular pathogens, and the generation of helper CD4+ T cells, which facilitate B cell activation and antibody production.[38]

In addition, transdermal nanovaccines can enhance the production of specific antibodies. B cells recognize the antigens presented by the antigen-presenting cells and differentiate into plasma cells, which secrete antigen-specific antibodies.[39] The sustained release and controlled delivery of antigens by nanovaccines can optimize the B-cell response and promote the production of high-affinity antibodies.

Preclinical and clinical efficacy studies

Preclinical and clinical efficacy studies play a crucial role in evaluating the effectiveness and safety of transdermal nanovaccines. These studies provide valuable insights into the vaccine's immunogenicity, protective efficacy, and potential adverse effects before progressing to human trials.[40]

In preclinical efficacy studies, transdermal nanovaccines are typically evaluated in animal models, such as mice, rats, or non-human primates. These studies assess the vaccine's ability to induce immune responses, including antigen-specific antibody production, T-cell activation, and cytokine release. Moreover, the protective efficacy of the vaccine can be evaluated by challenging animals with the target pathogen or assessing surrogate markers of protection. Pre-clinical studies also help identify optimal vaccine formulations, adjuvants, and delivery strategies.[41]

Once promising preclinical results are obtained, transdermal nanovaccines can proceed to clinical efficacy studies. Phase I, II, and III clinical trials are conducted to assess the safety, immunogenicity, and efficacy of the vaccine in human subjects. These trials involve larger cohorts of participants and carefully controlled study designs. Immunogenicity assessments may include measuring antibody responses, cellular immune responses, and immune memory. Clinical efficacy studies may involve evaluating the vaccine's ability to prevent infection, reduce disease severity, or confer long-term protection.[39]

Pre-clinical and clinical efficacy studies provide critical evidence for regulatory approval and subsequent deployment of transdermal nanovaccines. The data generated from these studies inform decision-making processes and contribute to the overall understanding of vaccine efficacy and safety. They are instrumental in guiding further research and development, refining vaccine formulations, and optimizing immunization strategies.

Comparative analysis of transdermal nanovaccines with traditional delivery methods

A comparative analysis between transdermal nanovaccines and traditional delivery methods reveals distinct advantages and considerations for each approach. Traditional delivery methods, such as intramuscular or subcutaneous injections, have been widely used for vaccine administration and offer several benefits. However, traditional injections can be associated with needle-associated pain, discomfort, and the need for skilled health-care professionals for administration. In addition, they may require needle disposal and pose potential risks of infection or needle stick injuries.[42,43]

On the other hand, transdermal nanovaccines offer unique advantages that make them an attractive alternative. Transdermal delivery eliminates the need for needles, providing a painless and needle-free vaccination experience. This approach enhances patient comfort and acceptance, particularly among individuals with needle phobia or those seeking convenient self-administration. Transdermal delivery also enables targeted delivery to immune-rich skin layers, which can lead to improved immune responses. Moreover, nanovaccines can be designed to provide controlled release and prolonged antigen exposure, potentially enhancing immune memory and reducing the need for frequent booster doses.[44]

However, there are considerations to address with transdermal nanovaccines. The skin's natural barrier limits the passage of large molecules, including antigens, necessitating the development of appropriate nanocarriers and delivery systems to enhance skin penetration. Formulation optimization, stability, scalability, and regulatory considerations are important factors in the development and commercialization of transdermal nanovaccines. Furthermore, the immune responses elicited by transdermal delivery may differ from those induced by traditional methods, warranting comparative studies to evaluate their immunogenicity and protective efficacy.[45]

FUTURE PERSPECTIVES AND CHALLENGES

Advancements in nanovaccine formulations and delivery systems

Advancements in nanovaccine formulations and delivery systems have propelled the field of vaccination forward, offering innovative approaches to enhance immune responses, improve vaccine efficacy, and address complex immunization challenges. Significant progress has been made in recent years, driven by advancements in nanotechnology and materials science.

One notable advancement is the development of novel nanocarrier systems for efficient antigen delivery. These nanocarriers, including lipid-based nanoparticles, polymer-based nanoparticles, and inorganic nanoparticles, provide platforms for encapsulating antigens and adjuvants. They offer benefits such as improved stability, controlled release, and enhanced immune cell targeting, optimizing antigen presentation and eliciting robust immune responses.[46]

Regulatory and safety considerations

Regulatory and safety considerations are critical aspects in the development and evaluation of transdermal nanovaccines. Regulatory agencies, such as the U.S. Food and Drug Administration and the European Medicines Agency, have specific guidelines and requirements for the approval of novel vaccine formulations.[47]

In addition, regulatory agencies require comprehensive data on the efficacy and immunogenicity of transdermal nanovaccines. Preclinical studies assess the vaccine's ability to induce specific immune responses and protective efficacy against the target pathogen. These studies provide important evidence to support the rationale for advancing to clinical trials.

Furthermore, regulatory agencies require comprehensive documentation, including data on preclinical and clinical studies, manufacturing processes, and quality control measures. These documents, along with robust safety and efficacy data, form the basis for regulatory submission and approval.[48]

Scaling up and commercialization challenges

Scaling up and commercializing transdermal nanovaccines present a set of challenges that need to be addressed for successful translation from the laboratory to widespread use. While nanovaccine formulations show promise in preclinical and early-stage clinical studies, several key considerations must be taken into account during the scaling up and commercialization process.

One major challenge is the optimization of manufacturing processes to achieve consistent and reproducible production at larger scales. The transition from small-scale laboratory synthesis to commercial manufacturing requires careful evaluation and optimization of formulation parameters, manufacturing techniques, and quality control measures. Robust and scalable manufacturing processes must be developed to ensure batch-to-batch consistency, product uniformity, and meeting regulatory requirements.[49]

Another challenge is ensuring the stability and shelf life of transdermal nanovaccines during storage and transportation. Nanovaccine formulations may be sensitive to environmental factors such as temperature, light, and humidity, which can affect their integrity and efficacy. Developing appropriate storage conditions and packaging strategies to maintain the stability of nanovaccines over extended periods is crucial for their commercial viability.

Commercialization also requires addressing the cost-effectiveness of transdermal nanovaccines. The materials and processes involved in nanovaccine production can be costly, and balancing the production costs with the final product's affordability is essential. Identifying cost-effective manufacturing strategies, optimizing production efficiency, and considering economies of scale are critical factors in ensuring the commercial viability and accessibility of transdermal nanovaccines.

Regulatory considerations pose another challenge in scaling up and commercializing transdermal nanovaccines. Meeting the stringent regulatory requirements and obtaining the necessary approvals from regulatory agencies are crucial for market entry. Adequate documentation, comprehensive safety and efficacy data, and adherence to regulatory guidelines are essential throughout the regulatory process.

Furthermore, market acceptance and adoption of transdermal nanovaccines may depend on factors such as public perception, health-care provider acceptance, and integration into existing vaccination programs. Addressing these factors requires comprehensive education and awareness campaigns, collaboration with health-care professionals, and demonstrating the benefits and value of transdermal nanovaccines in preventing disease and improving vaccination outcomes.[50]

CONCLUSION

Nanovaccines for transdermal delivery systems have gained significant attention in recent years due to their potential to revolutionize vaccine administration. The use of nanotechnology in vaccine development allows for precise control over the delivery, release, and targeting of antigens, enhancing their immunogenicity and efficacy. Here, an overview of the current state and future perspectives of nanovaccines for transdermal delivery systems has been provided. Lipid-based nanocarriers hold significant potential as transdermal delivery systems for nanovaccines. Their ability to protect, enhance penetration, provide sustained release, and offer versatility in vaccine formulation makes them promising candidates for improving vaccine efficacy and patient experience.

The current research indicates several advantages to this approach, including enhanced immune responses, improved patient compliance due to painless administration, and the

potential for self-administration. In addition, transdermal delivery systems offer a non-invasive alternative to traditional injection-based methods, reducing the risk of needle-related injuries and infections. Looking ahead, the future of nanovaccines through transdermal delivery holds even greater promise. Continued research efforts are expected to focus on refining nanocarrier design, optimizing antigen presentation, and further enhancing the immunogenicity of these formulations. Moreover, advancements in targeted delivery mechanisms and surface modifications may enable precise control over vaccine delivery, leading to personalized vaccination strategies tailored to individual immune responses.

However, challenges remain, including ensuring the safety and stability of nanovaccine formulations, addressing regulatory considerations, and scaling up production processes for widespread use. Addressing these challenges will require collaborative efforts across disciplines, including nanotechnology, immunology, pharmacology, and regulatory science.

In summary, while the field of nanovaccines through transdermal delivery is still in its early stages, it holds significant promise for revolutionizing vaccine administration. With continued research and innovation, nanovaccines delivered through transdermal drug delivery systems have the potential to improve vaccination strategies, enhance public health outcomes, and contribute to the global fight against infectious diseases. Nanovaccines represent a paradigm shift in vaccine development, harnessing the potential of nanotechnology to optimize immune responses and enhance vaccine efficacy. Their ability to mimic pathogens, target specific immune cells, provide sustained release, and accommodate combination vaccines positions them as promising tools in the prevention and control of infectious diseases. Continued research and development in nanovaccine technology hold great promise for advancing immunization strategies and addressing global health challenges.

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Source of Support: Nil. **Conflicts of Interest:** None declared.