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Innovations in Drug Delivery Systems: Exploring Nanoparticles and Targeted Therapies for Enhanced Immunotherapy

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Abstract

Background: The immune system plays a critical role in maintaining homeostasis and defending against diseases. However, imbalances can lead to conditions such as autoimmunity and cancer. Recent advances in immunotherapy have highlighted the need for improved drug delivery systems to enhance therapeutic efficacy while minimizing side effects.

Methods: This study reviews contemporary research on nanostructured drug delivery systems, focusing on the design and engineering of nanoparticles. A comprehensive literature search was conducted across scientific databases, including PubMed and ScienceDirect, utilizing keywords such as “nanotechnology,” “immunotherapy,” and “drug delivery.”

Results: Nanoparticles have emerged as promising carriers for drug delivery, leveraging their unique properties—such as size, surface area, and responsiveness to stimuli—to optimize the targeting and release of therapeutic agents. Various types of nanoparticles, including lipid-based, polymeric, and carbon-based systems, have been explored for their immunomodulatory capabilities. Notably, lipid nanoparticles have been effective in mRNA delivery for cancer therapies, while polymeric nanoparticles have shown enhanced solubility and bioavailability for immunotherapeutic agents.

Conclusion: The integration of nanoparticles in drug delivery systems represents a significant advancement in immunotherapy, offering improved targeting and efficacy against cancer and other diseases. However, challenges remain in ensuring specificity and minimizing long-term immunogenicity.

Continued research and clinical trials are essential to fully realize the potential of these innovative technologies in therapeutic applications.

Keywords: Nanoparticles, Drug Delivery, Immunotherapy, Targeted Therapy, Cancer Treatment.

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1. Introduction

The immune system is a complex network of defensive systems essential for sustaining homeostasis. These processes have developed to eliminate foreign chemicals and diseases, safeguarding the body from such risks. However, specific imbalances may arise, resulting in atypical immunological responses due to heightened conditions of immunosuppression or immunostimulation [1-3]. The immune system consists of both innate and adaptive defensive systems. Innate immunity functions as the primary defense against infections, initiating local inflammation via the activation of diverse immune cells and the production of cytokines. This reaction often triggers the activation of the adaptive immune system, whereby T and B cells, essential components of antigen-specific immunity and immunologic memory, engage pathogens [2,4]. Immune imbalances may present as autoimmunity, autoinflammation, allergies, or lymphoproliferation [5].

Misdirected immune responses, sometimes referred to as immunopathology, result in the immune system attacking host components. Recent studies indicate that the presentation of antigens significantly affects both inflammatory processes (immune activation) and immunological tolerance (unresponsiveness to self or benign foreign antigens). Inadequate immunological activation may result in detrimental reactions, including autoimmune illnesses, whereby the immune system targets the body's own tissues. Conversely, allergic disorders arise from hypersensitivity to ordinarily benign environmental chemicals [2]. Moreover, deficient immune responses might render the host susceptible to infections, neoplasms, and other detrimental agents. This reaction is often marked by the immune system's inability to adequately identify or react to pathogens or aberrant cells, resulting in the organism's vulnerability to dangers such as persistent infections or cancer [6,7]. This underscores the fragile equilibrium the immune system must maintain between hyperactivity (causing immunopathology) and hypoactivity (leading to immunodeficiency or insufficient protection).

Therapeutically manipulating the immune system has significant potential for treating chronic illnesses, including cancer and autoimmune disorders [8,9]. Immunotherapy offers a method to treat previously deemed deadly conditions and extend patient life by modulating innate and/or adaptive immunity [10]. Cancer immunotherapies, although demonstrating remarkable lasting responses, often result in either a lack of response (primary resistance) or recurrence after an initial response (acquired resistance) (Figure 1) [11-14]. Response rates are particularly poor in prevalent malignancies such as breast, prostate, and colon, and even within treatment same patient, distinct tumors may have disparate results [11].

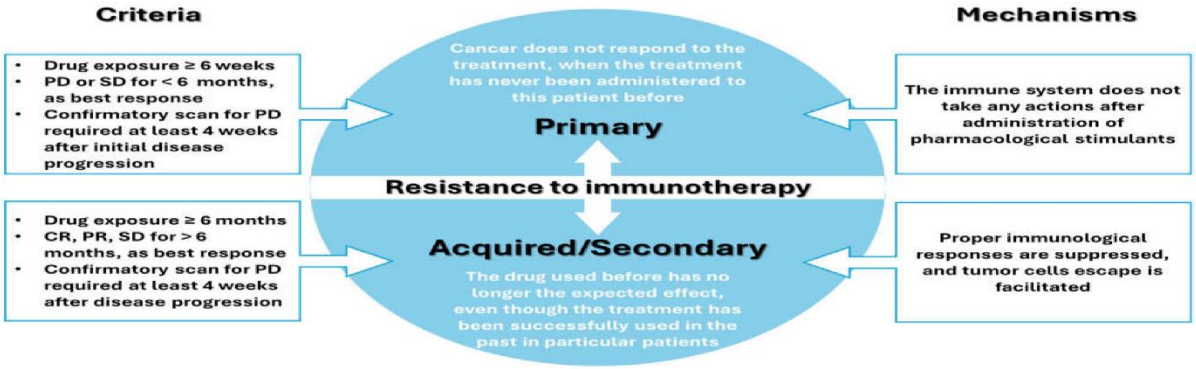

Figure 1. A concise comparison of primary and acquired resistance to immunotherapy [12-14].

The immune system is meticulously managed by checkpoints and filters to sustain immunological tolerance and avert damage from autoreactive cells. Nonetheless, autoimmune illnesses and malignant diseases persist often, perhaps owing to the evolutionary compromise between immunoprotection and

immunopathology, in addition to tactics used by parasites to circumvent the immune response [1]. Immunotherapeutic strategies may address these disorders; however, minimal success has been shown in instances when patients demonstrate initial resistance to immune checkpoint inhibitors (ICIs). ICI resistance has been attributed to either the ineffectiveness of immunotherapy in eliciting an anticancer immune response or the inability to mitigate tumor-induced immunosuppression, with many parameters associated with discrepancies in ICI efficacy (Figure 2) [13].

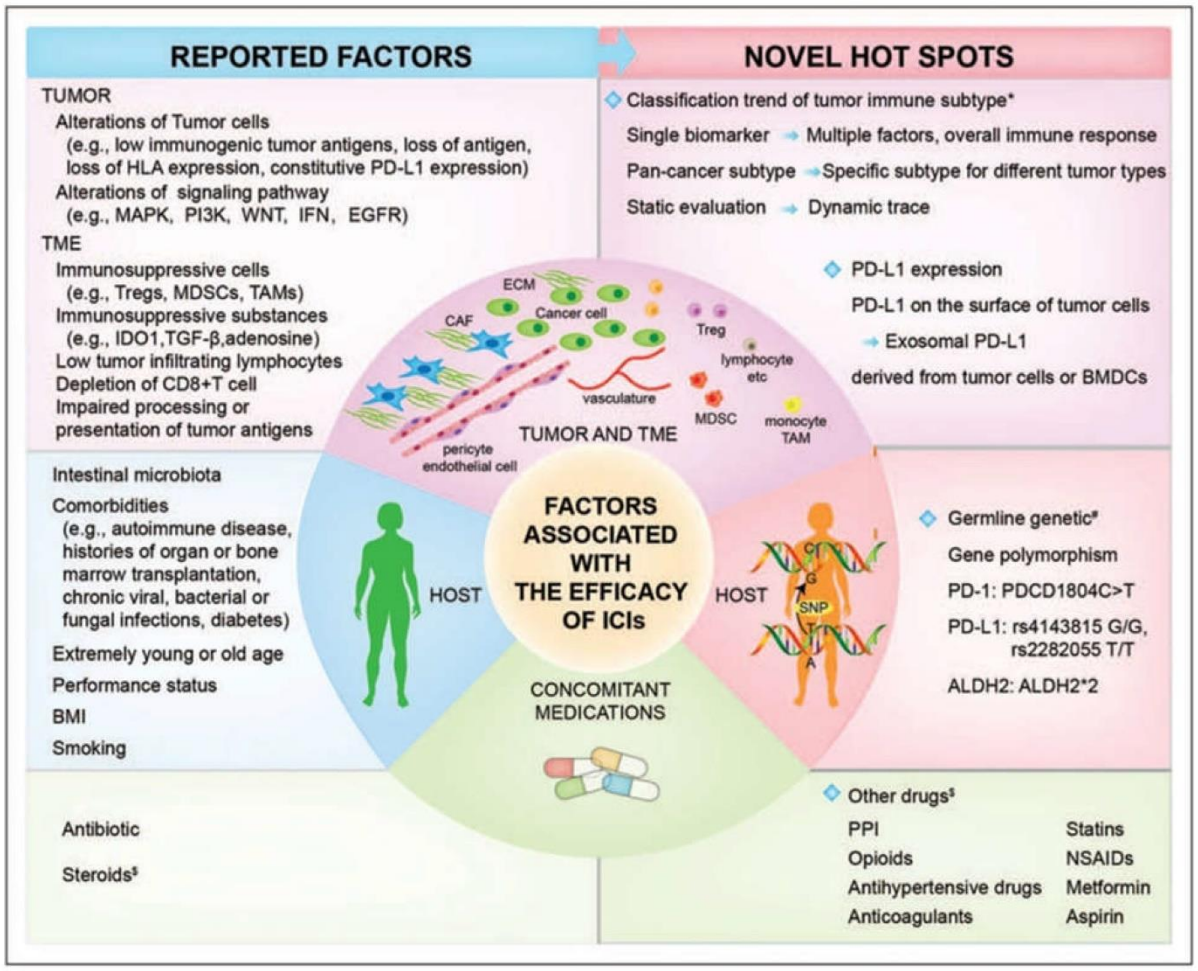

Figure 2. Concise overview of documented variables and emerging hot areas for immune checkpoint inhibitor treatment [13].

However, the main challenge in immunotherapy is achieving regulated control to ensure therapeutic efficacy without adverse side effects. Success depends on the precise administration of immunomodulators at the appropriate time and location, targeting specific tissues, cells, and intracellular sites. Notwithstanding the considerable advancements in immunotherapy, the efficacy of these therapies is sometimes impeded by challenges in targeting particular sites and regulating their release. Nanoparticles are being thoroughly examined as possible solutions to these challenges, including improved control of the time and site of immunotherapy administration [8,9,15].

Scientific literature has documented nanoengineered delivery vehicles using a diverse array of materials. Nanoparticles can serve as carriers for intriguing molecules, leveraging either their inherent characteristics or their capacity to react to various exogenous and/or endogenous stimuli [10,15]. Furthermore, nanomaterials may engage with the immune system in intricate manners, including various immune cells, signaling pathways, and physiological processes [16].

This study reviews contemporary research on nanostructured drug delivery systems in immunotherapy, emphasizing the potential benefits of designed nanoplatforms and their prospective uses in disease

treatment. This study reviews pertinent current research publications in English from these interrelated disciplines. Research was obtained from scientific databases, including Science Direct, PubMed, MDPI, ClinicalTrials.gov, and Google Scholar.

2. Design and Engineering of Nanostructured Pharmaceutical Delivery Systems

A multitude of nanomaterials has been produced recently, greatly increasing nanotechnology and expanding its applications across several fields. Nanostructured systems have been acknowledged as significant assets in biomedicine, garnering heightened attention for therapeutic applications [16-19]. Biomedical nanotechnology, which encompasses the design and manufacturing of advanced biomaterials and drug delivery systems, is especially adept at the precise targeting of the immune system [8,20].

In the context of therapeutic transport, nanostructured devices enhance the delivery of insoluble medicines, optimizing their bioavailability and minimizing the necessary dose. The quantity of administered medicine may be reduced by 100 to 1000 times when conveyed via targeted systems to the specified place or cells. Smaller quantities of active medicinal components may be provided as they are released only at the target site, eliminating drug losses to non-target tissues. Consequently, nanocarrier methodologies enhance localized medication concentrations while reducing adverse effects [21-24]. In addition to their tailored dimensions and morphologies, customized nanoparticles demonstrate improved permeability and retention effects, elevated thermal conductivity, and significant electromagnetic radiation absorption [25]. Furthermore, nanoparticles may integrate several therapeutic techniques to develop multifunctional treatment modalities or include both therapeutic and diagnostic capabilities to produce theranostics [9,21,26].

Nanomaterials possess dimensions that are very tiny, measuring between 1 to 100 nanometers in at least one aspect. Their dimensions are similar to some bacteria and viruses, enabling them to engage with the immune system in ways that resemble natural pathogens [8,27]. Their dimensions are beneficial for traversing intact physiological barriers and targeting particular sites for the release of carrying drugs. Consequently, nanoparticles engage with immune cells at a molecular level, resulting in either immunostimulatory or immunosuppressive responses, thereby regulating the immune system and facilitating their use for therapeutic reasons [8,18,27]. Conversely, immune cells influence nanoparticles, affecting their persistence, disintegration, and clearance [8].

Considering these beneficial features, nanoparticles have begun to be investigated for use in immune-based treatments aimed at a variety of disorders. Nanosystems engage with the immune system intricately, affecting many immune cells, including antigen-presenting cells (APCs), B cells, and T cells, and may elicit both humoral and cell-mediated immune responses. Interactions may be precisely optimized by modifying nanoparticles with certain physicochemical characteristics—such as dimensions, morphology, surface area, and charge—to improve their identification and absorption by immune cells, therefore successfully regulating the immune response [3,16]. Upon introduction into biological systems, nanoparticles (NPs) are identified as exogenous substances and may either activate or inhibit the immune response, contingent upon their chemical composition. The dual potential of nanoparticles to modify the immune response is essential for their therapeutic applications, enabling precise regulation of immunological activity in disease prevention and therapy [2,8].

The innate immunomodulatory capabilities of nanoparticles, together with their adaptability as nanocarriers, may provide exceptional results in the delivery of immunotherapeutic drugs via nanostructured systems. Diverse nanoparticles can be utilized for the delivery of immunomodulatory drugs to designated immune cell compartments, potentially emulating natural immune functions or inducing drug release via various stimuli (chemical reactions, thermodynamic alterations, magnetic fields, etc.) [8,28,29]

Nanoparticles possess potential anti-tumor properties and characteristics that make them valuable as therapeutic agents or vaccine adjuvants. Attributes like as dimensions, surface charge, functionalization, hydrophobicity or hydrophilicity, and the ability to bind various biomolecules significantly influence

nanoparticle biocompatibility with certain immune cells. Nanomaterials may be engineered to replicate certain foreign signals, alter the adaptive immune response, and establish novel biological systems for use in immunotherapy. However, certain features of nanoparticles have been shown to induce significant immunotoxicity, including the activation of stress-related genes, membrane rupture, oxidative stress, and the production of pro-inflammatory cytokines [3,30-32]. Consequently, the selection and creation of materials with suitable properties for immunotherapy need a comprehensive methodology.

Initially, silica and metal-based nanoparticles were used due to their capacity to elicit a specific immune response, either directly or indirectly, via linked antibodies or pharmaceuticals. Metal nanoparticles, including gold nanoparticles, are nondegradable, which may result in bioaccumulation. In contrast, silica nanoparticles necessitate surface functionalization to improve biocompatibility, and their impact on immune cells depends on their size, structure, and other physical characteristics [3]. Consequently, while these inorganic nanomaterials were initially popular, contemporary research has shifted towards creating delivery strategies for immunotherapeutic drugs using organic nanoparticles.

Polymers are an attractive category of materials for the production of nanocarriers, including a diverse array of polymeric nanoparticles that exhibit biocompatibility, biodegradability, solubility, stability, and versatility. Polymer-based nanostructures, whether used alone, in mixtures, or in conjunction with other materials, serve as carriers for diverse cargos (e.g., pharmaceuticals, genetic material, vaccines, biomolecules, imaging agents, etc.), enhancing therapeutic efficacy while reducing off-target toxicity [33,34]. Furthermore, polymeric structures might enhance immunotherapeutic strategies owing to their modifiable physicochemical characteristics and the potential for functionalization with various surface ligands. Polymeric nanoparticles can specifically target dendritic cells, essential for starting immunological responses, making them particularly advantageous for immunotherapeutic approaches. Moreover, research indicates that optimizing the dimensions, morphology, surface charge, and hydrophobic characteristics of nanoparticles facilitates the delivery of immunotherapeutic drugs to tumors. This meticulous regulation enables the integration of immunotherapy modalities, prevents tumor recurrence, fosters the establishment of enduring immunological memory, and enhances patient outcomes by reducing toxicity and unfavorable effects related to the immune system [34,35].

Lipid nanoparticles (LNPs) have intriguing opportunities in immunotherapy. LNPs have been thoroughly studied due to their capacity for large-scale production while allowing for meticulous control over their shape and lipid content [36-38]. Their use in tumor immunotherapy has significantly improved the efficacy of anti-tumor treatments while reducing adverse effects on the whole body. LNPs were shown to be effective carriers for mRNA delivery in cancer immunotherapy. LNPs safeguard mRNA and enhance its uptake and dispersion inside cells. From a therapeutic standpoint, lipid nanoparticles (LNPs) have successfully facilitated the delivery of mRNA, as shown by their role in COVID-19 vaccines [39-41].

Carbon-based nanomaterials (CBNs) have been extensively investigated for their potential in conveying diverse medicines, using their distinctive properties to modulate the immune system. Carbon-based nanomaterials (CBNs) include several types, such as graphene/graphene oxide (GO) nanosheets, single/multi-walled carbon nanotubes (SWCNTs/MWCNTs), and fullerenes, each exhibiting distinct characteristics regarding induced immunological responses [3,18,42]. GO nanoparticles have been extensively studied for medicinal applications, including as medication delivery, cancer treatment, photodynamic therapy, and vaccine antigen delivery, among others. Reports indicate that GO may stimulate the immune system by enhancing inflammatory factors and promoting the proliferation and differentiation of lymphocytes. Nevertheless, GO has cytotoxic properties and may induce DNA damage owing to its lateral dimensions and oxidation state, necessitating surface functionalization for enhanced compatibility as nanocarriers and adjuvants [43]. MWCNT was shown to elicit cellular responses by producing oxidative stress, disrupting lysosomal membranes, increasing the permeability of 3T3 fibroblasts, bronchial epithelial cells, and RAW macrophages, ultimately leading to death in the affected cells. SWCNTs were shown to influence malignant cells by inducing NF-kB and p38 activation, as well as reactive oxygen species

(ROS) generation [44]. Consequently, given the intrinsic potential of CBNs, they may be used in conjunction with medicinal cargo to provide synergistic effects.

Recently, DNA and RNA nanostructures have surfaced as interesting instruments in biomedicine, particularly in medication delivery. The self-assembly characteristics of these nucleic acids enable the construction of diverse designs, including polygons, nano-cubes, prisms, nano-rings, and other structures such as three-way and four-way junctions. Tetrahedral DNA nanostructures (TDNs) have garnered significant interest among various 2D and 3D forms, primarily owing to their straightforward synthesis, exceptional stability, superior biocompatibility, and ease of functionalization. The beneficial characteristics of TDNs render them appropriate for the transportation and regulated release of chemotherapeutics, nucleic acids, imaging probes, immunotherapeutic agents, and theranostics [45].

Moreover, hybrid nanomaterials, consisting of at least two components with distinct compositions and properties, usually organic and inorganic, have been intentionally engineered to exhibit synergistic activities and considerable potential in augmenting cancer immunotherapy [46]. Consequently, several synergistic systems have been documented in recent literature, each exhibiting varying levels of effectiveness and distinct immunotherapeutic uses.

3. Nanostructured Systems for Cancer Immunotherapy

Cancer immunotherapy, which adjusts the immune system to target tumors, has resulted in prolonged life in previously fatal instances [10,13]. Combinatorial strategies have shown beneficial in improving immunotherapeutic results by targeting several pathways in the cancer immunity cycle [47,48]. Recent advancements concentrate on mitigating tumor-induced immune suppression, using therapies such immune checkpoint inhibitors (ICIs) that target the CTLA-4, PD-1, and PD-L1 pathways. These techniques serve as significant options for the treatment of solid and hematological malignancies, specifically addressing the evasion mechanisms within the tumor microenvironment [49-51]. However, despite the progress shown throughout trials, several problems persist. ICI-based treatments demonstrate restricted effectiveness owing to fast drug clearance and off-target toxicity, which may potentially result in resistance to immunotherapeutic drugs in some individuals [12,13,52,53]. Immunotherapy stimulates the host immune system but may unintentionally induce detrimental side effects by activating non-tumor-specific immune cells [54].

There is growing evidence in cancer immunotherapy about the significance of Toll-like receptors (TLRs). Toll-like receptors (TLRs) are a kind of pattern recognition receptor (PRR) that identify pathogen-associated and damage-associated molecular patterns, hence initiating innate immune responses [10,15,55]. The TLR7 and TLR8 located on the surface of endosomes are particularly significant for cancer therapeutic applications. These receptors may elicit type 1 interferons and inflammatory responses via the MyD88 pathway [10]. Consequently, the injection of TLR agonists, such imiquimod and resiquimod, may elicit immunological responses and activate cytotoxic T-cells. Nonetheless, obstacles include inadequate solubility, adverse effects, and immunological resistance restrict their clinical use. Furthermore, the immune system may acquire resistance to TLR activation, progressively reducing the effectiveness of TLR7/TLR8 agonist therapies [10,15,56].

In this perspective, nanotechnology-based drug delivery methods are seen as viable strategies to improve the effectiveness of TLR7/8 agonists in cancer immunotherapy. The use of diverse nanocarriers, particularly for tiny molecular immunotherapeutics, may reduce dose-limiting toxicities and improve treatment results [10,15,25]. Nanocarriers, including nanocapsules, nanoemulsions, and micelles, enable targeted administration, improve lymphatic transport, and prolong drug release, thereby sustaining effective doses while minimizing toxicity [10]. Advancements in nanoparticle engineering improve the targeted absorption and concentration of cancer cells in malignant tissues, possibly overcoming current limitations in immunotherapy and fostering advantageous interactions between nanoparticles and immune cells [53,56].

A compelling method for administering TLR agonists involves the use of poly(esteracetal)s, which provide the requisite chemical characteristics for pH-responsive drug release [74]. Bixenmann et al. [15] created self-assembling micelles using amphiphilic mPEG-b-P(MDO) poly(esteracetal) block copolymers capable of delivering an immune stimulatory TLR-7 agonist (i.e., Adifectin). This nanosystem facilitated enhanced solubilization of the delivered medication, providing effective delivery, pH-controlled release, and preservation of receptor activation. Dias et al. [57] suggested the use of polymeric nanoparticles containing imiquimod as a substitute for the commercial medication formulation. The nanoparticles exhibited markedly superior antiangiogenic efficacy and diminished tumor size and quantity relative to the commercial formulation and controls, suggesting that the polymeric nanocarriers improve treatment results by augmenting skin permeation and solubility of the immunotherapeutic agents for cutaneous cancers. Gazzi et al. [58] have developed a pectin-based hydrogel nanocapsule as an alternate delivery vehicle for imiquimod in the treatment of melanoma. This work demonstrated that the engineered nanosystem facilitated drug penetration across all epidermal layers and resulted in an enhanced cytotoxic impact of imiquimod on the examined tumor cell types, indicating significant promise for advancing immunotherapy for this condition. The efficacy of imiquimod may be enhanced with its encapsulation in nanoemulsions, as shown by Frank et al. [59]. The researchers evaluated the nanoformulation for cervical cancer, demonstrating its enhanced antitumoral efficacy relative to the free medication, which is ascribed to the synergistic processes of autophagy and apoptosis.

Multiple nanoformulations have been suggested for the administration of resiquimod. Rodell et al. [60] suggested encapsulating this TLR agonist into β-cyclodextrin nanoparticles to facilitate its effective transport to tumor-associated macrophages. The scientists integrated this technique with the injection of the immune checkpoint inhibitor anti-PD-1, achieving synergistic outcomes for immunotherapy response rates. In contrast, Widmer and colleagues [61] developed a resiquimod delivery method using PLGA/mPEG-PLA nanoparticles that are absorbed by dendritic cells and macrophages, therefore enhancing anticancer immune responses. In vivo experiments conducted on mice shown that the nanoformulation effectively targets lymph nodes and enhances cancer immunotherapy results.

An alternative method for eliciting robust immune responses is the precise delivery of particular nucleic acids to tumor locations. These gene delivery methods facilitate the absorption of therapeutic cargo, which subsequently activates cellular and humoral immune responses, leading to tumor elimination [39]. Komura et al. [62] advocated the use of guanosine- and uridine-rich single-stranded RNA (GU-rich RNA) as a medicinal agent, identified as an agonist of TLR7 and TLR8. The researchers developed a nanostructured hydrogel assembly of GU-rich RNA/DNA designed for sustained release. The delivery mechanism was well internalized in murine dendritic cells, eliciting significant immunostimulatory activity, and is thus regarded as a useful adjuvant in cancer immunotherapy.

4. Clinically Endorsed Nanostructured Pharmaceutical Delivery Systems

Nanostructured drug delivery systems have garnered considerable interest in immunotherapy, with many formulations obtaining FDA clearance. LNP-based and liposomal pharmaceuticals are notably distinguished by their biocompatibility, drug-loading capability, and potential to mitigate toxicity. Doxil®, the first FDA-approved nanodrug (1995), exemplifies the use of PEGylated liposomes to improve doxorubicin administration in cancer therapy. Other sanctioned formulations using liposomes as nanocarriers, like Myocet®, DaunoXome®, and Onivyde®, have been created to address different malignancies, providing extended circulation duration and less adverse effects. LNPs were pivotal in the creation of mRNA vaccines during the COVID-19 pandemic, as shown by Comirnaty™ and Spikevax®, showcasing the adaptability of nanotechnology in contemporary medicine [63,64].

Polymer-based nanostructured drug delivery systems have been investigated in immunotherapy; nevertheless, fewer formulations have obtained regulatory clearance compared to lipid-based alternatives. An such case is Abraxane®, an albumin-bound nanoparticle formulation authorized in 2005 for the administration of paclitaxel in the treatment of several malignancies. Furthermore, polymer micelle-based nanosystems such as Genexol®, Nanoxel®, and Apealea® have been engineered for the administration of

paclitaxel or docetaxel in the treatment of advanced malignancies, providing better solubility, less toxicity, and improved drug transport to tumor locations. These polymeric systems, in conjunction with lipid-based nanoparticles, highlight the significant potential of nanostructured drug delivery systems in addressing malignant diseases, providing novel insights for enhancing immunotherapeutic treatment options and fostering optimism for the clinical application of under-researched formulations [33,63,64].

5. Conclusions

Nanostructured drug delivery technologies used in immunotherapy have shown significant potential in improving the efficacy and specificity of therapies, particularly in cancer applications. The inherent immunomodulatory characteristics and adaptability of nanoparticles as carriers might markedly improve the efficacy of nanostructured systems in administering immunotherapeutic drugs, as shown by various research in the domain. Crucial characteristics like as dimensions, surface charge, functionalization, and the capacity to bind various biomolecules significantly affect their biocompatibility with certain immune cells. By replicating certain foreign signals, nanoparticles may alter the adaptive immune response, facilitating the creation of novel biological systems for immunotherapy.

However, other obstacles persist, including specificity concerns, the immunogenicity of various nanomaterials, ambiguous long-term safety, and production expenses. Continuous attempts are being made to address these limitations, with emerging trends indicating that while nanostructured drug delivery technologies in immunotherapy show significant potential, the area remains in development. Limited clinical investigations have examined the administration of immunotherapy by drug delivery systems, particularly in the context of cancer and infectious disorders. Therefore, enhancing the clinical trials system and introducing novel formulations for clinical evaluation is imperative. Furthermore, nanostructured drug delivery systems for other immunotherapeutic applications should be evaluated in forthcoming clinical studies to broaden the range of treatments for various medical problems, including autoimmune illnesses and allergic and inflammatory disorders.

In conclusion, nanostructured drug delivery methods provide a robust foundation for advancements in immunotherapy. Interdisciplinary cooperation and ongoing enhancement will be crucial to surmount existing obstacles and fully actualize the promise of these new treatment methodologies.

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الابتكارات في أنظمة توصيل الأدوية: استكشاف الجسيمات النانوية والعلاجات الموجهة لتحسين العلاج المناعي

الملخص

الخلفية :يلعب الجهاز المناعي دورًا حاسمًا في الحفاظ على التوازن ومكافحة الأمراض. ومع ذلك، يمكن أن تؤدي الاختلالات في الجهاز المناعي إلى حالات مثل أمراض المناعة الذاتية والسرطان. أبرزت التطورات الحديثة في العلاج المناعي الحاجة إلى أنظمة توصيل أدوية محسنة لتعزيز الفعالية العلاجية وتقليل الآثار الجانبية.

الطرق :تستعرض هذه الدراسة الأبحاث المعاصرة حول أنظمة توصيل الأدوية النانوية، مع التركيز على تصميم وهندسة الجسيمات النانوية. تم إجراء بحث شامل في قواعد بيانات علمية، مثل PubMed وScienceDirect، باستخدام كلمات مفتاحية مثل "تكنولوجيا النانو"، "العلاج المناعي"، و"توصيل الأدوية."

النتائج :ظهرت الجسيمات النانوية كناقلات واعدة لتوصيل الأدوية، مستفيدة من خصائصها الفريدة، مثل الحجم، ومساحة السطح، والاستجابة للمحفزات، لتحسين استهداف وإطلاق العوامل العلاجية. تم استكشاف أنواع مختلفة من الجسيمات النانوية، بما في ذلك الأنظمة القائمة على الدهون، والبوليمرات، والكربون، لقدراتها على تعديل المناعة. على وجه الخصوص، أثبتت الجسيمات النانوية الدهنية فعاليتها في توصيل mRNA لعلاجات السرطان، في حين أظهرت الجسيمات النانوية البوليمرية تحسينًا في الذوبانية والتوافر البيولوجي للعوامل العلاجية المناعية.

الاستنتاج :يمثل دمج الجسيمات النانوية في أنظمة توصيل الأدوية تقدمًا كبيرًا في العلاج المناعي، مما يوفر استهدافًا محسّنًا وفعالية ضد السرطان وأمراض أخرى. ومع ذلك، لا تزال التحديات قائمة لضمان الخصوصية وتقليل المناعية طويلة المدى. البحث المستمر والتجارب السريرية ضرورية لتحقيق الإمكانات الكاملة لهذه التقنيات المبتكرة في التطبيقات العلاجية.

الكلمات المفتاحية :الجسيمات النانوية، توصيل الأدوية، العلاج المناعي، العلاج الموجه، علاج السرطان.