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Nanotechnology-Based Drug Delivery Systems for Chemotherapy: A Review of Current Approaches and Future Prospects

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Abstract

Nanotechnology-based drug delivery systems have developed as a novel approach to cancer treatment, notably chemotherapy, with higher precision, efficacy, and less side effects than traditional approaches. Chemotherapy, while successful in targeting rapidly dividing cancer cells, frequently encounters considerable hurdles such as systemic toxicity, non-targeted drug distribution, and resistance. Nanotechnology offers a promising alternative for targeted delivery, controlled release, and overcoming multidrug resistance (MDR). Various nanocarriers, such as liposomes, polymeric nanoparticles, dendrimers, and metallic nanoparticles, have been developed to improve drug delivery by leveraging the increased permeability and retention (EPR) effect for tumour targeting. The design of these nanocarriers, which includes size, surface qualities, and functionality, provides longer circulation time, increased tumour formation, and fewer side effects on healthy tissues. Despite multiple clinical achievements, such as the FDA's clearance of nanomedicines like Doxil and Abraxane, there are still obstacles in translating these technologies from laboratory research to clinical practice. Nanoparticle stability, scalability, regulatory barriers, and cytotoxicity are all important considerations. This study examines the current state of nanotechnology-based drug delivery systems, emphasizing clinical accomplishments, problems, and upcoming technologies such as stimuli-responsive and AI-assisted drug delivery systems. The future of cancer treatment is in the creation of smart nanocarriers that can combine chemotherapy with other therapeutic modalities such as immunotherapy, gene therapy, and photodynamic therapy. Hence, personalized nanomedicine, which tailors drug delivery systems to individual patients' genetic profiles and tumour features, is a promising future direction. Overall, this review seeks to investigate the most recent developments and future prospects in nanotechnology-driven chemotherapy.

Keywords: Nanotechnology; Drug delivery systems; Chemotherapy; Cancer treatment; Pharmacokinetics.

1. Introduction

1.1. Overview of Cancer Treatment Challenges, Particularly Chemotherapy

Chemotherapy is one of the most popular therapeutic approaches for cancer, and it has changed over decades. Chemotherapy targets rapidly dividing cells, which are a characteristic of cancer, with cytotoxic medications that inhibit cell division and proliferation. Despite its efficiency in destroying cancer cells, chemotherapy poses substantial hurdles. One of the main problems is the inability to distinguish between healthy and malignant cells, as the medications also affect quickly dividing normal cells in the bone marrow, gastrointestinal tract, and hair follicles. This causes adverse effects such as neutropenia, nausea, and alopecia, lowering the quality of life for people undergoing treatment (Gottesman, 2002).

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Furthermore, chemotherapy has significant challenges due to cancer's heterogeneity. Tumours are frequently made up of a heterogeneous population of cells with various genetic abnormalities, resulting in differential responses to treatment. This complexity can lead to partial cancer cell eradication, allowing for resistance, recurrence, and metastasis (Vogelstein et al., 2013). As a result, researchers are constantly looking for innovative therapeutic approaches to overcome these hurdles and improve the efficacy of cancer treatment.

1.2. Current Limitations of Conventional Chemotherapy: Systemic Toxicity, Drug Resistance, and Non-targeted Delivery

One of the most significant disadvantages of conventional chemotherapy is its systemic toxicity, which results from the non-selective nature of chemotherapeutic agents. These medications go through the circulation and harm both malignant and healthy cells. For example, doxorubicin, a popular chemotherapeutic drug, is renowned for its cardiotoxicity, which limits its usage in individuals with prior heart problems (Minotti et al., 2004). Furthermore, medicines like cisplatin produce nephrotoxicity, ototoxicity, and neurotoxicity, resulting in serious long-term side effects (Pabla et al., 2008).

Drug resistance is another big issue. Cancer cells can develop resistance through a variety of methods, including increased drug efflux, altered drug targets, or improved DNA repair pathways (Holohan et al., 2013). This commonly results in therapy failure and disease progression. Multidrug resistance (MDR) is especially problematic in recurring malignancies, where subsequent chemotherapeutic regimens are ineffective (Szakács et al., 2006).

Finally, non-targeted drug distribution in traditional chemotherapy lowers therapeutic efficacy. The majority of chemotherapeutic drugs circulate throughout the body, with only a small fraction reaching the tumour site. The inability to target medications specifically to cancer cells not only raises systemic toxicity but also lowers the therapeutic index (Allen et al., 2004). Targeted drug delivery strategies are thus an important area of study for improving chemotherapy outcomes while reducing collateral damage to healthy tissues.

1.3. Rationale for Nanotechnology in Drug Delivery: How Nanotechnology Can Enhance Chemotherapy Effectiveness and Reduce Side Effects

Nanotechnology provides a viable answer to conventional chemotherapy's shortcomings by allowing for more precise medication delivery while decreasing systemic side effects. Nanoparticles, which range in size from 1 to 100 nanometres, can be designed to transport chemotherapeutic drugs and release them directly at the tumour site, increasing therapy efficacy (Peer et al., 2020). One of the primary benefits of nanoparticles is their ability to take advantage of the enhanced permeability and retention (EPR) effect, which occurs when tumour vasculature is more permeable than normal blood vessels, allowing nanoparticles to accumulate preferentially in cancerous tissues (Maeda et al., 2000).

Nanoparticles can be functionalized with targeting ligands that bind selectively to cancer cell receptors, such as folic acid or transferrin receptors, to increase targeting specificity (Davis et al., 2008). This active targeting lowers the drug's effects on healthy cells while increasing its concentration at the tumour site. In addition to targeted delivery, nanoparticles enable regulated drug release, allowing for sustained therapeutic levels over longer periods of time and reducing drug administration frequency (Mohanraj et al., 2006).

Nanotechnology also provides techniques for overcoming multidrug resistance (MDR). Researchers can overcome cancer cells' drug efflux pumps by encapsulating chemotherapy medications into nanoparticles, increasing the drug's intracellular concentration and potency (Batrakova et al., 2008). For example, polymeric nanoparticles laden with doxorubicin have been found to overcome resistance mechanisms in MDR cancers by allowing for direct intracellular drug release (Torchilin, 2011).

1.4. Purpose of the Review: To Explore Current Approaches in Nanotechnology-Based Drug Delivery Systems and Assess Future Directions

The goal of this analysis is to look at existing efforts in nanotechnology-based drug delivery systems for chemotherapy and evaluate their future possibilities. Given the encouraging outcomes of nanoparticle-based medication delivery in preclinical and clinical trials, a thorough examination of the many types of nanocarriers, their mechanisms of action, and clinical applications is required (Shi et al., 2017). This review will look at the several types of nanomaterials that are currently utilized in chemotherapy, such as liposomes, polymeric nanoparticles, metallic nanoparticles, and dendrimers, and highlight their benefits and drawbacks.

Furthermore, the review will examine the existing limits of nanotechnology in chemotherapy, such as potential toxicity, stability concerns, and difficulties in large-scale production and clinical translation. Although nanoparticle-based drug delivery systems have showed considerable promise, there are still obstacles to overcome before they can become mainstream in cancer treatment (Hare et al., 2017). To provide a thorough grasp of the field, regulatory issues, safety concerns, and cost-effectiveness will all be explored.

This review explores emerging technologies in nanomedicine, such as stimuli-responsive nanoparticles, which release drugs in response to specific triggers like pH, temperature, or magnetic fields, and personalized nanomedicine, which tailors drug delivery systems to individual patients' needs (Lammers et al., 2012). These innovations hold the potential to revolutionize cancer treatment by providing more effective, less toxic, and patient-specific therapies.

1.5. Research Objectives

This review aims to assess the impact of nanotechnology on improving chemotherapy medication delivery. This study seeks to deliver a thorough overview by identifying existing methodologies, evaluating their effects on treatment efficacy and safety, and highlighting current problems. The investigation of forthcoming innovations will underscore the prospective expansion and revolutionary influence of nanotechnology in cancer treatment.

- To evaluate and classify existing nanotechnology-based drug delivery methods utilised in chemotherapy.
- To evaluate the advantages of nanotechnology in improving drug effectiveness and reducing chemotherapy adverse effects.
- To ascertain the obstacles related to nanotechnology-driven medication delivery in chemotherapy.
- To investigate prospective innovations and forthcoming trends in nanotechnology for targeted cancer treatment.

1.6. Research Questions

This review aims to examine critical questions regarding the use of nanotechnology in the delivery of chemotherapeutic drugs. Given the breakthroughs in nanotechnology that indicate potential for more effective and targeted cancer therapies, it is essential to examine existing methodologies, assess their benefits, and recognise the challenges they encounter. Moreover, comprehending forthcoming prospects in this domain can elucidate how nanotechnology might revolutionise cancer treatment in the future.

- What are the contemporary nanotechnology-based medication delivery technologies employed in chemotherapy?
- In what ways do nanotechnology-based systems enhance the efficacy and diminish the adverse effects of chemotherapeutic agents?
- What are the principal problems and constraints associated with the application of nanotechnology in chemotherapeutic medication delivery?
- What prospective advancements and improvements are expected in nanotechnology-based medication delivery for chemotherapy?

2. Nanotechnology in Drug Delivery: An Overview

2.1. Definition and Significance of Nanotechnology in Medicine

Nanotechnology is the manipulation of materials on a molecular or atomic scale, typically between 1 and 100 nanometres. Nanotechnology has emerged as a transformative tool for diagnosing, treating, and preventing a wide range of diseases, including cancer. Its capacity to design and construct nanoscale materials opens new avenues for better drug delivery by increasing therapeutic agent bioavailability, solubility, and pharmacokinetics (Farokhzad et al., 2009). Nanotechnology-based drug delivery methods provide more accuracy in targeting sick tissues, especially in chemotherapy, where localized drug administration reduces systemic side effects while increasing therapeutic efficacy (Peer et al., 2020).

The significance of nanotechnology in medicine stems from its ability to improve drug delivery by providing more effective treatments with fewer side effects. Nanoparticle-based systems, for example, can overcome biological barriers like the blood-brain barrier, which has traditionally limited drug delivery to specific tissues (Blanco et al., 2015). Furthermore, nanoparticles can be designed to deliver various therapeutic drugs at the same time, enabling combination therapies that target cancer cells via distinct mechanisms.

2.2. Key Characteristics of Nanocarriers

2.2.1. Size and Surface Properties

Nanocarriers' biological interactions and medication delivery efficacy are heavily influenced by their size and surface characteristics. Nanoparticles typically range in size from 10 to 100 nanometres, allowing them to circulate in the bloodstream for longer periods of time and enter tissues more effectively than larger particles (Moghimi et al., 2001). Their small size allows them to accumulate in tumours via the increased permeability and retention (EPR) effect, which takes advantage of tumour tissue's leaky vasculature (Maeda et al., 2000). Furthermore, nanocarrier surface features such as charge and hydrophilicity affect their stability, biodistribution, and immune system interaction (Danhier et al., 2010).

Nanocarriers' surface modification, such as polyethylene glycol (PEG) coating, can increase their biocompatibility by lowering immune recognition and increasing circulation time. This mechanism, known as PEGylation, improves nanoparticle therapeutic potential by increasing the possibility of their accumulating at the tumour site (Owens & Peppas, 2006).

2.2.2. Enhanced Permeability and Retention (EPR) Effect

The EPR effect is a critical property that differentiates nanocarrier-based medication delivery from traditional chemotherapy. Tumour vasculature has wide fenestrations and inadequate lymphatic outflow, which allows nanoparticles to concentrate passively in tumour tissues while avoiding normal tissues (Maeda et al., 2000). This action allows nanoparticles to deliver larger concentrations of medications to cancer cells, increasing efficacy while decreasing systemic toxicity. However, the EPR effect is not consistent across different cancers, and tumor size, location, and vascularization can all influence its efficacy (Torchilin, 2011).

2.2.3. Controlled and Targeted Drug Release

Nanocarriers allow for controlled and targeted drug release, enhancing the specificity and effectiveness of chemotherapy. Controlled release refers to the ability of nanoparticles to release their drug payloads over a prolonged period, maintaining therapeutic drug levels in the body and reducing the frequency of drug administration (Jain, 2008). Additionally, targeted drug release can be achieved by functionalizing the surface of nanocarriers with ligands that bind to specific receptors on cancer cells. For example, nanoparticles conjugated with folic acid or antibodies can selectively bind to cancer cells overexpressing folate receptors or specific antigens, respectively (Davis et al., 2008).

2.3. Types of Nanomaterials Used in Drug Delivery

Table 1 Types of Nanomaterials Used in Drug Delivery

Types	Description
Liposomes	Liposomes are spherical vesicles made up of lipid bilayers that can encapsulate both hydrophilic and hydrophobic drugs. As one of the earliest nanocarrier systems developed for drug delivery, they have shown significant potential in enhancing the pharmacokinetics of chemotherapeutic agents (Allen & Cullis, 2013). The liposomal formulation Doxil, which encapsulates doxorubicin, became the first FDA-approved nanomedicine for cancer therapy and demonstrated a reduction in cardiotoxicity compared to free doxorubicin (Gabizon et al., 2003). To further improve their performance, liposomes can be functionalized with PEG, which extends circulation time and decreases immune system clearance (Sercombe et al., 2015).
Polymeric Nanoparticles	Polymeric nanoparticles are solid colloidal particles manufactured from biodegradable and biocompatible polymers like PLGA and PCL (Soppimath et al., 2001). These nanoparticles have various advantages, including excellent stability, regulated drug release, and the capacity to prevent drug degradation (Zhang et al., 2008). Polymeric nanoparticles can be designed to release drug payloads in response to certain stimuli, such as pH or temperature changes, making them ideal for targeted cancer treatment (Kumar et al., 2013).
Dendrimers	Dendrimers are extremely branching, tree-like polymers that can be carefully designed to transport medicines, imaging agents, and targeting moieties. Their distinct structure, which includes a central core, branching units, and terminal functional groups, provides a large surface area and multivalency for drug conjugation (Kannan et al., 2014). Dendrimers have been studied as carriers for chemotherapeutic drugs such as methotrexate and doxorubicin due to their ability to increase

	medication solubility and bioavailability (Yiyun et al., 2005). Dendrimers can also be functionalized with targeting ligands to increase drug delivery selectivity (Kesharwani et al., 2014).
Metallic Nanoparticles (e.g., Gold and Silver)	Metallic nanoparticles, particularly gold and silver nanoparticles, have sparked interest in cancer therapy because of their unique optical and thermal properties (Huang et al., 2007). Gold nanoparticles can be coupled with medications or targeting ligands to deliver chemotherapeutic treatments directly to cancer cells (Jain et al., 2012). Gold nanoparticles can also be employed in photothermal therapy to kill cancer cells by generating heat when exposed to near-infrared light (Ghosh et al., 2008). Silver nanoparticles, known for their antibacterial capabilities, have also been studied for their ability to improve chemotherapy efficacy (Gupta et al., 2014).
Carbon-based Materials (e.g., Carbon Nanotubes)	Carbon nanotubes (CNTs) are cylindrical nanostructures made up of graphene sheets folded into tubes. Their unique structural features, such as large surface area and mechanical strength, make them intriguing drug delivery candidates (Lacerda et al., 2006). CNTs can be functionalized with medicines, peptides, or targeting ligands, allowing for controlled and targeted drug release (Bianco et al. 2005). However, worries concerning CNT toxicity and biocompatibility persist, and additional study is required to ensure their safe usage in clinical applications (Chou et al., 2012).
Micelles	Micelles are nanoscale structures that self-assemble from amphiphilic molecules. They have a hydrophilic head and a hydrophobic tail. Micelles can encapsulate hydrophobic medicines in their core, increasing the solubility and bioavailability of chemotherapeutic medications that are weakly water soluble (Kwon & Forrest, 2006). Polymeric micelles, such as those composed of polyethylene glycol-poly (lactic acid) (PEG-PLA), have shown promise in delivering pharmaceuticals such as paclitaxel, an insoluble anticancer agent (Gaucher et al., 2005). Micelles can also be functionalized for targeted distribution, increasing their potential as nanocarriers for cancer treatment.

3. Mechanisms of Action for Nanotechnology-Based Chemotherapy

3.1. Targeted Drug Delivery: Active vs. Passive Targeting

Nanotechnology-based drug delivery systems (DDS) offer the potential for both passive and active Nanotechnology-based drug delivery systems (DDS) can deliver chemotherapeutic drugs directly to tumour cells while limiting damage to healthy tissue through both passive and active targeting. Passive targeting largely makes use of the enhanced permeability and retention (EPR) effect, which permits nanoparticles to collect in tumour tissues due to leaky vasculature and inadequate lymphatic drainage (Maeda et al., 2000). This action allows nanoparticles, such as liposomes and polymeric nanoparticles, to enter tumour locations passively. However, because of its heterogeneity among tumour types, the EPR effect alone is not always sufficient (Torchilin, 2011).

Active targeting, on the other hand, entails loading nanoparticles with ligands that recognize specific receptors overexpressed on cancer cells. Folate-conjugated nanoparticles, for example, target folate receptors, which are often overexpressed in ovarian and lung malignancies (Zwicke et al., 2012). Such receptor-mediated targeting guarantees that nanoparticles exclusively bind to cancer cells, boosting therapeutic efficiency while lowering systemic toxicity (Gu et al., 2007).

3.2. Drug Loading and Release Kinetics: Sustained Release Mechanisms and Control Over Bioavailability

The regulated and sustained release of chemotherapeutic drugs from nanocarriers is an important property that promotes bioavailability and reduces side effects. Drug release kinetics from nanoparticles can be fine-tuned by modifying the nanocarrier's composition and structure. For example, polymeric nanoparticles constructed of poly (lactic-co-glycolic acid) (PLGA) allow for the slow and sustained release of encapsulated medicines due to the progressive degradation of the polymer matrix (Danhier et al., 2012).

Liposomes, another well-studied nanocarrier, may encapsulate both hydrophilic and hydrophobic medicines, and their drug release can be regulated by changing their lipid content and surface features (Barenholz, 2012). Thermosensitive liposomes, which release their drug cargo in response to localized hyperthermia, are one example of a controlled release mechanism being investigated in clinical trials (Li et al., 2015).

3.3. Endocytosis and Cellular Uptake: How Nanoparticles Interact with Tumour Cells

Nanoparticles can enter tumour cells through a variety of endocytic mechanisms, including clathrin-mediated endocytosis, caveolae-mediated endocytosis, and macropinocytosis (Sahay et al., 2010). Once absorbed, nanoparticles

are usually carried to endosomes and lysosomes, where they can release their therapeutic payloads. The surface charge and size of nanoparticles are important determinants in determining their absorption by cancer cells. Positively charged nanoparticles, for example, interact more easily with negatively charged cell membranes, increasing cellular absorption (Zhang et al., 2008). The application of surface ligands on nanoparticles for active targeting can enhance receptor-mediated endocytosis, allowing tumour cells to efficiently internalize therapeutic drugs (Zwicke et al., 2012).

3.4. Overcoming Multidrug Resistance (MDR): Nanocarrier-Based Solutions

Multidrug resistance (MDR) is a significant barrier in chemotherapy because cancer cells can expel medications through overexpressed efflux pumps such P-glycoprotein (P-gp) (Gottesman, 2002). Nanocarriers provide a promising solution to MDR by shielding medicines from efflux pumps and increasing intracellular drug concentration. For example, PLGA-based polymeric nanoparticles have been found to circumvent efflux pumps, resulting in higher intracellular drug concentrations and cytotoxicity in resistant cancer cells (Boman et al., 1996).

Furthermore, some nanocarriers, such as those functionalized with P-gp inhibitors or siRNA, might directly control MDR processes, improving the efficiency of chemotherapeutic drugs in resistant cancers (Patel et al. 2013).

4. Current Approaches in Nanotechnology-Based Drug Delivery for Chemotherapy

4.1. Liposome-Based Drug Delivery Systems: Case Studies (e.g., Doxil)

Liposomes, one of the first nanocarrier systems designed for drug delivery, have shown promising results in chemotherapy. Doxil, a PEGylated liposomal formulation of doxorubicin, was the FDA's first approved nanomedicine and continues to serve as a model for liposomal drug delivery (Barenholz, 2012). Doxil decreases the systemic toxicity of free doxorubicin by encapsulating it in liposomes, while also improving its pharmacokinetic profile. Clinical trials have demonstrated that Doxil is particularly effective in the treatment of ovarian cancer, Kaposi's sarcoma, and breast cancer (Barenholz, 2021).

4.2. Polymer-Drug Conjugates and Polymeric Nanoparticles

Polymeric nanoparticles, such as PLGA-based systems, have received a lot of interest for their biocompatibility, biodegradability, and ability to encapsulate a variety of chemotherapeutic drugs (Danhier et al., 2012). Polymer-drug conjugates, which contain a chemotherapeutic agent covalently bonded to a biodegradable polymer, improve drug solubility and stability, allowing for controlled and sustained drug release. Paclitaxel-loaded PLGA nanoparticles, for example, have been found in preclinical trials to be more effective against solid tumours.

4.3. Metallic Nanoparticles in Chemotherapy: Applications, Successes, and Challenges

Metallic nanoparticles, specifically gold, silver, and iron oxide nanoparticles, have been extensively studied for their potential in chemotherapy. Gold nanoparticles, for example, can be combined with chemotherapeutic medicines and targeting ligands to improve drug delivery specificity and therapeutic efficacy (Huang et al., 2007). Furthermore, gold nanoparticles can be used in photothermal therapy, where they generate heat when exposed to light, successfully destroying cancer cells (Ghosh et al. 2008). However, issues such as toxicity, biocompatibility, and scale-up manufacturing must be solved before they are widely used in clinical settings (Jain et al., 2012).

4.4. Dendrimers: Architecture, Biocompatibility, and Therapeutic Potential

Dendrimers are highly branching, tree-like nanocarriers with a well-defined architecture that enables exact control of their size, surface characteristics, and functionalization. Their distinct structure allows for substantial drug loading and multivalency, making them suitable carriers for chemotherapeutic drugs such as methotrexate and doxorubicin (Yiyun et al., 2005). Dendrimers can also be modified with targeting ligands to improve drug delivery specificity, making them a promising platform for cancer therapy (Kesharwani et al., 2014).

4.5. Hybrid Systems: Combining Multiple Nanomaterials for Synergistic Effects

Hybrid nanocarrier systems, which mix several nanomaterials, have the potential for synergistic effects in chemotherapy. For example, gold-coated liposomes or polymeric nanoparticles can benefit from both liposomes' drug-carrying capability and gold nanoparticles' photothermal characteristics (Liu et al., 2015). Preclinical investigations have demonstrated that combining chemotherapy with heat therapy can increase tumour destruction (Park et al., 2017).

4.6. Surface Modification Techniques: PEGylation and Ligand Conjugation

Surface modification of nanoparticles, particularly PEGylation, is critical for increasing nanocarrier circulation duration and lowering immune clearance (Owens & Peppas, 2006). PEGylated nanoparticles can avoid the mononuclear phagocyte system, increasing the chances of reaching the tumour location. In addition to PEGylation, ligand conjugation, such as the addition of folate or transferrin, promotes active targeting of tumour cells, increasing the therapeutic efficacy of nanocarriers (Zwicke et al. 2012).

5. Clinical Successes and Challenges

5.1. FDA-approved nanomedicines for chemotherapy

The development of nanomedicines has resulted in FDA approval of many nanoparticle-based drug delivery systems, which have had a significant influence on cancer treatment. Doxil, a liposomal version of doxorubicin, is a notable example, as it was the first FDA-approved nanomedicine for cancer treatment. Doxil's success is primarily due to its ability to optimize drug pharmacokinetics, reduce cardiotoxicity, and improve therapeutic results by targeting tumour tissues using the increased permeability and retention (EPR) effect (Barenholz, 2012). Another example is Abraxane, an albumin-bound paclitaxel nanoparticle formulation authorized for the treatment of breast, lung, and pancreatic cancer. Abraxane outperforms standard paclitaxel in terms of drug solubility, intratumoral concentration, and lower hypersensitivity reactions (Yardley, 2013). These approved nanomedicines demonstrate the potential of nanotechnology to improve the delivery and efficacy of chemotherapy drugs.

5.2. Challenges in clinical translation

Despite the success of FDA-approved nanomedicines, there are still obstacles in clinical translation of nanotechnology-based drug delivery systems. One key challenge is nanoparticle stability, which must be maintained during manufacturing, storage, and administration. Nanoparticle aggregation and early drug release can impair efficacy and safety (Zhang et al., 2008). Another problem is scalability; manufacturing nanoparticles in large quantities while maintaining consistent quality is difficult due to the intricate and sensitive nature of nanoparticle production.

Regulatory difficulties complicate the process further because there are no defined rules for nanomedicine approval, and extra evidence on toxicity, pharmacokinetics, and biodistribution is frequently necessary (Ventola, 2017). Patient safety is also a problem, as nanoparticle accumulation in non-target organs can result in detrimental consequences that may not be detected until long-term studies are undertaken.

5.3. Toxicological concerns

Toxicological concerns with nanomedicines are a major concern in clinical development. The cytotoxicity of nanomaterials varies with their size, shape, surface characteristics, and composition. For example, while gold nanoparticles have shown promise as drug delivery vehicles, their long-term accumulation in tissues can cause oxidative stress and organ damage (Khlebtsov & Dykman, 2011). Furthermore, the breakdown of polymeric nanoparticles might produce hazardous byproducts that can trigger inflammation or immunological responses (McNamara & Tofail, 2017). Long-term exposure to nanomaterials has generated concerns about their potential for chronic toxicity, as some nanoparticles can remain in the body for extended periods of time. Nanomedicines' clinical success depends on their biocompatibility and low toxicity.

6. Emerging Technologies and Future Prospects

6.1. Stimuli-responsive drug delivery systems

Nanomedicine's emerging technologies include stimuli-responsive drug delivery systems, which release medications in reaction to specific environmental triggers such as pH, temperature, or magnetic fields. pH-sensitive nanoparticles, for example, use the acidic tumour microenvironment to selectively release chemotherapeutic drugs at the tumour site while preserving healthy tissues (Mu et al., 2021). Thermoresponsive nanoparticles are engineered to release medications when subjected to mild hyperthermia, giving targeted treatment to heated tumour regions (Li et al., 2010). Magnetically triggered systems use external magnetic fields to direct magnetic nanoparticles to the tumour and control drug release in a non-invasive way (Liu et al., 2019). These stimuli-responsive systems offer a potential method to providing regulated drug administration while minimizing off-target effects.

6.2. Personalized nanomedicine

Personalized medicine is changing cancer therapy by tailoring therapies to unique patient profiles, and nanotechnology is expected to play a key part in this transformation. Personalized nanomedicine entails creating nanoparticles that target biomarkers or genetic alterations specific to a patient's cancer. This method permits the delivery of highly targeted medicines that improve efficacy while minimizing side effects (Shi et al., 2017). For example, nanoparticles functionalized with antibodies or ligands that identify overexpressed receptors on cancer cells might selectively transport chemotherapeutic drugs to tumour cells while sparing healthy organs. Personalized nanomedicine has enormous potential for improving treatment outcomes, especially in tumours that are difficult to treat with traditional chemotherapy.

6.3. Smart nanoparticles

Smart nanoparticles are the next generation of drug delivery devices, combining modern technologies like artificial intelligence (AI) and nanorobots to improve medication release precision and control. AI-assisted systems can monitor real-time data on a patient's therapeutic response and change drug dose or release rates as needed (Das, 2023). Nanorobots, which are tiny objects that can travel the body and accomplish specialized jobs, are being studied for their ability to deliver medications directly to tumour cells or remove hazardous compounds from the bloodstream (Ummat et al., 2016). These smart nanoparticles have the potential to transform cancer therapy by delivering real-time, adaptable treatment techniques that boost efficacy while minimizing negative effects.

6.4. Nanocarriers for combination therapies

Nanocarriers are also being developed for combination therapies, which combine several treatment methods including chemotherapy, immunotherapy, gene therapy, and photodynamic therapy. Co-delivering several therapeutic compounds within a single nanoparticle can result in synergistic effects that improve treatment success (Chandratre, 2014). For example, combining chemotherapeutic drugs with immune checkpoint inhibitors in nanoparticle formulations has shown promise for increasing anti-tumour immune responses (Qi et al., 2017). Similarly, nanoparticles can transport gene-editing tools like CRISPR-Cas9 to fix genetic mutations in cancer cells while also delivering chemotherapeutic medicines (Wang et al. 2021). These combination medicines provide a diverse approach to addressing cancer's complexity, with the ability to overcome resistance mechanisms and improve patient outcomes.

6.5. Prospects in overcoming resistance and improving targeting

Overcoming drug resistance remains a major difficulty in chemotherapy, and novel nanotechnology-based techniques are being explored to solve it. One interesting approach is the use of exosome-based delivery devices. Exosomes are naturally occurring nanoparticles that facilitate intercellular communication and can be designed to deliver chemotherapeutic drugs to resistant cancer cells (Jang et al., 2013). Exosomes have the benefit of being biocompatible and less likely to elicit immunological reactions than manufactured nanoparticles. Another cutting-edge strategy uses CRISPR-modified nanoparticles to deliver gene-editing tools to target and change drug-resistance genes (Yin et al., 2019). These novel approaches have promising opportunities for enhancing targeting, overcoming resistance, and eventually advancing cancer therapy.

7. Conclusion

Nanotechnology-based drug delivery systems are changing the face of chemotherapy by overcoming major limitations of traditional cancer treatments such as systemic toxicity, lack of selectivity, and drug resistance. Liposomes, polymeric nanoparticles, dendrimers, and metallic nanoparticles, among others, have shown the potential to transform cancer treatment by enhancing drug transport, bioavailability, and targeting while minimizing side effects. The FDA's clearance of numerous nanomedicines, notably Doxil and Abraxane, demonstrates nanocarriers' clinical success in increasing chemotherapy efficacy. However, clinical translation of these nanomedicine platforms poses difficulties due to nanoparticle stability, regulatory licensing, large-scale manufacture, and long-term safety issues. These obstacles highlight the necessity for more extensive clinical trials and uniform regulatory frameworks to assure the safe and effective use of nanotechnology-based medication delivery systems. Emerging technologies like stimuli-responsive nanoparticles, AI-assisted systems, and tailored nanomedicine show enormous potential for the future. Stimuli-responsive drug delivery systems that respond to environmental cues such as pH or temperature provide precise control over drug release, whilst AI and smart nanoparticles enable real-time modifications in medication therapy. Furthermore, integrating chemotherapy, immunotherapy, gene therapy, and photodynamic treatment in hybrid nanocarrier systems may improve therapeutic outcomes by targeting numerous cancer pathways at once. Personalized nanomedicine, which tailors treatment to unique patient profiles and tumour features, is a promising approach to overcome resistance and enhancing treatment specificity. Hence, nanotechnology-based drug delivery systems provide

a potent and adaptable foundation for the future generation of chemotherapy. Continued research and innovation in this field will be critical to overcoming present difficulties and realizing nanotechnology's full potential for cancer treatment, ultimately enhancing patient outcomes and quality of life.

Compliance with ethical standards

Disclosure of conflict of interest

The authors have no conflict of interest to be disclosed.

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