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NANOPARTICLE-BASED TARGETED DRUG DELIVERY FOR THE TREATMENT OF HEMATOLOGICAL DISORDERS

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ABSTRACT

Nanoparticles have emerged as a highly advanced and promising drug delivery system (DDS) for the treatment of hematological disorders, including anemia, leukemia, and hemophilia. Traditional therapeutic approaches often involve systemic drug administration, which can lead to suboptimal drug distribution and adverse side effects. In contrast, nanoparticle-based drug delivery offers targeted and controlled release, enhancing therapeutic efficacy while minimizing systemic toxicity. This review highlights the design and application of various nanoparticles, including polymeric nanoparticles, dendrimers, liposomes, and metallic nanoparticles, in delivering therapeutic agents directly to diseased blood cells, such as red blood cells, leukocytes, and platelets. The phospholipid bilayer-based nanocarriers are particularly effective in encapsulating and transporting both hydrophilic and hydrophobic drugs. We also discuss recent advancements in nanoparticle engineering, biocompatibility, and functionalization strategies that allow selective targeting of pathological sites. Preclinical and clinical studies demonstrate the significant potential of nanomedicine in revolutionizing treatment paradigms for blood-related disorders. Moreover, ongoing innovations in nanoscale drug delivery technologies hold promise for improving patient outcomes and reducing the burden of chronic hematological conditions.

Introduction

Nanotechnology, rooted in the disciplines of physics and materials science, has emerged as a transformative field with profound implications in biology, biotechnology, and medicine. The term "nanoparticle" refers to particles typically ranging from 1 to 100 nanometers in at least one dimension. Historically, the study of colloidal systems—particle dispersions between molecular solutions and coarse suspensions—laid the foundation for nanoscience (Hauser et al., 1955). The concept of colloidal size (1–1000 nm), proposed over a century ago, remains relevant and widely accepted in contemporary material sciences (Le Chatelier et al., 1999; McNaught & Wilkinson, 1997). The integration of nanotechnology into drug delivery has revolutionized the way therapeutic agents are transported and released within the human body. Traditional drug delivery systems (DDS), although foundational to modern pharmacotherapy, exhibit several limitations in pharmacokinetics and pharmacodynamics. These include rapid clearance, enzymatic degradation, off-target toxicity, and low bioavailability (Tibbitt et al., 2016; Builders et al., 2016). Drugs administered via conventional routes (oral, intravenous, nasal, or mucosal) often display uncontrolled release, non-specific distribution, and systemic side effects, which hinder their therapeutic efficacy (Li et al., 2022; Vlachopoulos et al., 2022). Moreover, challenges such as mucosal barriers, pH variability, and first-pass metabolism further compromise drug activity and reduce patient compliance (Alshammari et al., 2022). To address these issues, advanced drug delivery platforms have been developed, including controlled-release systems such as biodegradable polymers, osmotic pumps, matrix tablets, and hydrogel-based carriers (Marco-Dufort et al., 2021; Smolensky et al., 2018). These approaches aim to enhance drug localization, minimize off-target effects, and extend drug half-life. However, these methods still fall short in achieving precise targeting at the cellular or molecular level, especially in the treatment of complex diseases such as cancer or hematological disorders (Mak et al., 2019). The conceptual foundation of nanotechnology in medicine was publicly introduced by Richard P. Feynman in 1959 in his landmark lecture, *"There's Plenty of Room at the Bottom"*. The field gained wider scientific traction with the publication of *Engines of Creation* by K. Eric Drexler in 1986, followed by Robert A. Freitas' *Nanomedicine* in 1999, which formalized the term and vision of using nanodevices for therapeutic and diagnostic purposes (Drexler, 1991; Freitas, 1999).

Nanomedicine is defined as the medical application of engineered nanostructures (typically 1–100 nm) for disease diagnosis, monitoring, treatment, and tissue regeneration (Kostarelos et al.,

2006). Due to their tunable surface properties, high surface-to-volume ratio, and ability to be functionalized with ligands, antibodies, or targeting moieties, nanoparticles enable site-specific drug delivery with improved cellular uptake, reduced immunogenicity, and controlled release profiles. These attributes make nanoparticles particularly advantageous in treating hematological disorders, which often involve systemic complications and require targeted intervention at the cellular level (Y. Liu et al., 2022). In recent years, several types of nanoparticles have been explored for therapeutic applications, including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, and metallic nanocarriers (e.g., gold, silver, or iron oxide nanoparticles). These nanocarriers can be engineered to deliver chemotherapeutic agents, anti-inflammatory drugs, or gene therapies specifically to affected blood cells—such as erythrocytes, leukocytes, or thrombocytes—thereby improving treatment efficacy and reducing systemic toxicity. Hematological disorders such as anemia, leukemia, and hemophilia continue to pose significant global health burdens, affecting millions of individuals and often requiring long-term and invasive therapies. Nanoparticle-based DDS offer a non-invasive, precise, and efficient alternative by enhancing drug solubility, stability, and bioavailability while reducing the need for frequent dosing and minimizing side effects.

This review explores the landscape of nanoparticle-mediated drug delivery for hematological disorders. We discuss the physicochemical properties of nanoparticles, their mechanisms of action, strategies for surface functionalisation, and preclinical and clinical evidence supporting their use. By evaluating current advancements and ongoing challenges, this review aims to provide insights into the future potential of nanomedicine as a cornerstone in the treatment of blood-related diseases.

2. Types and classification of nanoparticles:

The development of nanoparticle-based drug delivery systems has significantly transformed therapeutic strategies by offering targeted, efficient, and controlled drug delivery, particularly in the context of complex disorders such as hematological diseases. With rapid advancements in biological nanotechnology, these systems have become a cornerstone of modern nanomedicine, offering innovative approaches to overcome the shortcomings of traditional drug delivery platforms, such as non-specific distribution, premature drug degradation, and systemic toxicity (Y.T. Liu et al., 2022). Nanoparticle-based drug delivery systems (NDDS) can be broadly

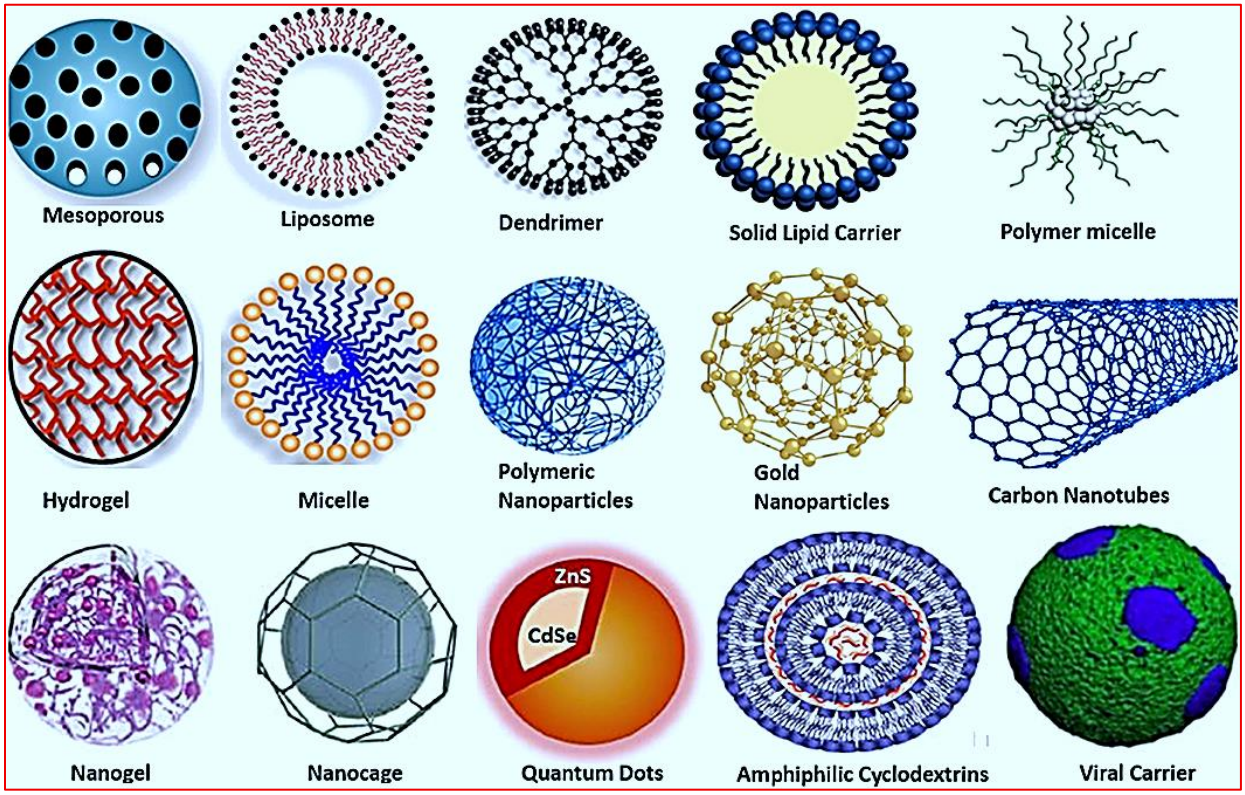
categorized into two main types based on their structural framework and design principles: carrier-based systems and carrier-free systems (X.Y. Liu et al., 2022).

Carrier-based nanoparticles are the most extensively utilized systems in drug delivery research. These are further sub-classified into organic and inorganic nanocarriers depending on the chemical composition and physicochemical behavior of the carrier material. Organic nanocarriers, which include polymeric nanoparticles, liposomes, and dendritic macromolecules, are widely recognized for their biocompatibility, biodegradability, and ability to encapsulate a wide range of therapeutic agents. Polymeric nanoparticles made from materials such as polylactic acid (PLA), polyglycolic acid (PGA), poly(lactic-co-glycolic acid) (PLGA), and natural polymers like chitosan, have been used to enhance drug solubility, improve pharmacokinetics, and achieve controlled release profiles. Liposomes, formed by lipid bilayers, can encapsulate both hydrophilic and lipophilic drugs, offering protection from enzymatic degradation and facilitating prolonged circulation. Similarly, dendritic macromolecules or dendrimers are highly branched polymers that allow multiple drug molecules or targeting ligands to be conjugated, increasing their targeting specificity and therapeutic index (K.F. Liu et al., 2018). On the other hand, inorganic nanocarriers provide enhanced structural rigidity and are often used in applications where imaging, diagnostics, or externally guided delivery (such as magnetic targeting) is desired. Notable inorganic nanoparticles include gold nanoparticles, which possess unique surface plasmon resonance (SPR) properties suitable for photothermal therapy and targeted drug delivery. Magnetic oxide nanoparticles, such as iron oxide-based systems, are often used in magnetic resonance imaging (MRI) and magnetic targeting of drugs. Silica nanoparticles, particularly mesoporous silica nanoparticles (MSNs), provide a high surface area and tunable pore sizes, enabling the loading of a diverse range of drugs, including large biomolecules like proteins and nucleic acids. Among the most studied inorganic nanocarriers are carbon nanotubes (CNTs), which have exceptional mechanical, thermal, and electrical properties. Their hollow tubular structure provides a high surface area for drug loading, while their surface can be functionalized with chemical groups or targeting ligands to improve solubility and biocompatibility (X.J. Liu et al., 2021).

Carrier-free nanoparticles, in contrast, are composed entirely of the active pharmaceutical ingredient (API) without any additional carrier matrix. These nanoparticles self-assemble into nanoscale structures due to the physicochemical properties of the drug molecules themselves. This strategy maximizes drug loading efficiency and eliminates potential toxicity associated with carrier

materials. Carrier-free systems are particularly advantageous for poorly water-soluble drugs, as the nanoscale formulation improves their solubility, bioavailability, and cellular uptake (X.Y. Liu et al., 2022). Overall, the selection between carrier-based and carrier-free systems—and within carrier-based systems, the choice of organic versus inorganic nanocarriers—depends on several factors, including the physicochemical properties of the drug, the biological barriers involved, the desired release kinetics, and the therapeutic application. As illustrated in **Figure 1**, these different nanoparticle systems address several critical limitations associated with conventional drug delivery methods, including poor targeting, rapid clearance, enzymatic degradation, and systemic toxicity (Y.T. Liu et al., 2022). Their advancement continues to pave the way for more effective, personalized treatment modalities in hematology and other medical fields, making them integral to the future of therapeutic innovation (K.F. Liu et al., 2018; X.J. Liu et al., 2021; X.Y. Liu et al., 2022).

Figure 2: Classification of different types of nanoparticles and their further categorisation (Karlioti et al., 2022).



3. History and Development of Nanoparticles

The history of nanoparticles (NPs) is deeply rooted in both ancient practices and modern scientific advancements. While the term "nanotechnology" is a product of the 20th century, humans have been unknowingly utilising nanomaterials (NMs) for thousands of years. For instance, over 4,500 years ago, ancient civilizations employed natural nanofibers such as asbestos in ceramic matrices to enhance durability and heat resistance (Heiliglag et al., 2013). Around 4,000 years ago, ancient Egyptians applied nanoscale lead sulfide (PbS) particles—synthesised through early chemical processes—for cosmetic and hair dye purposes (Walter et al., 2006). These early uses illustrate the intuitive exploitation of nano-sized materials, long before the underlying science was formally understood. A pivotal moment in the scientific history of nanoparticles came in 1857, when Michael Faraday synthesised a colloidal solution of gold nanoparticles, demonstrating their unique optical properties. His observations laid the foundation for understanding nanoparticle behavior at the quantum scale (Mie et al., 1908), marking the formal birth of nanoscience in modern chemistry and physics. The 20th and 21st centuries witnessed a surge in nanotechnology research, with the focus shifting toward biomedical and therapeutic applications. Particularly in drug delivery, nanoparticles have revolutionized the field by allowing precise, site-specific treatment with improved efficacy and minimized side effects.

The beginning of the 21st century marked a turning point for nanoparticle-based drug delivery systems. In 2000, liposomal nanoparticles were introduced as a promising vehicle to enhance the targeted delivery of anticancer drugs to tumors, significantly improving treatment outcomes in ovarian carcinoma (Zhang et al., 2008). This was quickly followed by the emergence of PEGylated polycyanoacrylate nanoparticles in 2001, which were found to be highly effective in delivering therapeutic molecules against prion diseases, primarily due to their extended circulation time and biocompatibility (May et al., 2013). As the field advanced, transferrin-mediated nanoparticles became critical for targeting drug delivery across the blood-brain barrier, offering a novel approach to treating brain cancers and neurological disorders (Collinge et al., 2005). Lipid-based nanoparticles, introduced in 2003, demonstrated significant success in treating hepatocellular carcinoma, hemophilia, and hepatitis B by efficiently targeting liver hepatocytes using mouse xenograft models (Ulbrich et al., 2009). Gold nanoparticles (AuNPs), recognized for their photothermal and targeting capabilities, gained prominence in 2004. They enabled tumor-specific drug delivery, particularly in MC-38 carcinoma models, and were often used in

combination with therapeutic agents such as tumor necrosis factor (Panyan et al., 2004; Ashihara et al., 2005). Their versatility and minimal toxicity made them a preferred choice for both diagnostic imaging and therapeutic applications.

In 2005–2006, the combination of folate-conjugated liposomes and starch nanoparticles emerged as a method to increase tumor selectivity, particularly in prostate and liver cancers. These systems showed promise for reducing toxicity and improving delivery of genetic materials like HSVtk/GCV in targeted gene therapy (Paciotti et al., 2006; Lu et al., 2002). The late 2000s brought new developments with chitosan, alginate, and mesoporous silica nanoparticles (MSNs). MSNs offered high surface area and tunable porosity, making them ideal carriers for chemotherapeutic agents like methotrexate. Their enhanced cellular uptake and site-specific delivery further advanced cancer treatment (Cheng et al., 2008). Simultaneously, silver nanoparticles found application in vector control for dengue and malaria, and later, in gene silencing therapies (Kohler et al., 2005; Mengesha et al., 2013). Their green synthesis methods using plants like *Panama pinnata* highlighted the growing emphasis on eco-friendly nanoparticle production (Jadoun et al., 2021). From 2010 to 2020, the diversity of nanoparticle systems expanded significantly. Diamond nanoparticles delivered small interfering RNAs for Ewing sarcoma, while polyamidoamine (PAMAM) dendrimers showed promise in malaria treatment (Sarmento et al., 2007; Minelli et al., 2010). Additionally, solid lipid nanoparticles, filamentous bacteriophage vectors, and electroporation-aided nanocarriers emerged as efficient strategies for gene and drug transfer in various viral, bacterial, and oncological diseases (Beg et al., 2017; Chamundeeswari et al., 2019).

During the COVID-19 pandemic, lipid-based and metal oxide nanoparticles (e.g., zinc oxide, silver oxide) played key roles in vaccine development. They enhanced the delivery, stability, and immune response of mRNA vaccines, such as Doxil and Onpattro (Garg et al., 2019). These breakthroughs underscored the potential of nanomedicine not only in oncology but also in controlling global pandemics. By 2022, novel materials like iridium oxide nanoparticles had entered the field, facilitating macromolecule-based drug delivery for cancer and neurodegenerative conditions. These new platforms continued to push the boundaries of therapeutic nanotechnology (Assa et al., 2017). Collectively, the timeline of nanoparticle development reflects a rapid evolution from rudimentary uses in ancient civilizations to sophisticated, highly targeted drug delivery systems in contemporary medicine. These innovations, summarized in **Table 1**, represent

a convergence of material science, biotechnology, and clinical medicine, positioning nanoparticles as essential tools in the next generation of therapeutics.

Table 1: Overview of Nanoparticles Used in Drug Delivery Systems from 2000 to 2022

Year	Types of Nanoparticles	Drug Delivery Approaches	Diseases	Application	Reference
2000	Liposome	Increases drug delivery to tumor	Ovarian carcinoma	Useful for human cancer cure	Zhang et al., 2008
2001	PEGylated polycyanoacrylate	Efficient carriers for therapeutic molecules	Prion diseases	Long retention time in PEGylated particles	May et al., 2013
2002	Transferrin-mediated endocytosis	Acts as receptor for drug/gene transfer via BBB	Brain and cancer	Tumor-specific anticancer drug	Collinge et al., 2005
2003	Lipid nanoparticles	Injection with green dye expresses HCC	Hemophilia, Hepatitis B, HCC	Targets hepatocyte cells in xenograft models	Ulbrich et al., 2009
2004	Gold nanoparticles	Vector for TNF, targets tumor sites	MC-38 carcinoma	Effective via intravenous injection	Panyan et al., 2004; Ashihara et al., 2005
2005	Liposome with folic acid	Conjugate liposomes deliver DNA	Prostate cancer	High transfection efficiency, HSVtK/GCV system	Paciotti et al., 2006
2006	Folate-conjugated starch	PEGylated folate-starch nanoparticles	Liver cancer	DOX toxicity reduction, liver-targeted therapy	Lu et al., 2002
2007	Gold nanoparticles (AuNPs)	Transfection with β-galactosidase	Nasopharyngeal carcinoma	Reduces toxicity, treats acute diseases	Yu et al., 2007
2008	PEGylated gold nanoparticles	Effective photodynamic cancer treatment	Cancer	Target-specific in vivo and in vitro delivery	—
2009	Chitosan/Alginate nanoparticles	Pre-gel polymer assembly with $CaCl_2$	—	Affects loading ability and particle size	Ghosh et al., 2008
2010	Mesoporous silica	Targeted carrier for MTX	Cancer	High specificity and cellular uptake	Cheng et al., 2008
2011	Diamond nanoparticles	siRNA transfer in Ewing sarcoma	Ewing sarcoma	Organized oligonucleotide delivery	Sarmento et al., 2007
2012	Silver nanoparticles	Designed larvicides for vector control	Dengue, Malaria	Derived from *Annona squamosa* leaves	Kohler et al., 2005
2013	Silver nanoparticles	Noble metal vector for drug delivery	Photoactivated gene silencing	Nuclease resistance, efficient uptake	Mengesha et al., 2013
2014	Green-synthesised silver nanoparticles	Synthesized from *Panama pinnata*	Dengue	Eco-friendly medicinal carrier	Jadoun et al., 2021
2015	Polyamidoamine	Carrier for malaria drug delivery	Malaria	Enhances solubility, reduces toxicity	Minelli et al., 2010
2016	Solid lipid nanoparticles	Used with electroporation	Colon cancer	Compresses therapeutic potential	Beg et al., 2017
2017	Filamentous bacteriophage	Phage-mediated drug/gene transfer	Viral, bacterial infections	Virus-based delivery system	Chamundeeswari et al., 2019

2018	Mesoporous silica with polymer	siRNA loading via electrostatic poration	—	Solves noxiousness and short half-life issues	Lamicchane et al., 2015
2019	Chitosan nanoparticles	Universal drug delivery	—	Vaccination, cancer, pulmonary/oral routes	Jahromi et al., 2021
2020	Folic acid-based mesoporous silica	pH-stable targeting system	Cancer	Encapsulates drug for site-specific action	Slita et al., 2018
2021	Lipid/metal oxide nanoparticles	Used in COVID-19 vaccines	SARS-CoV-2	Doxil and Onpattro-based systems	Garg et al., 2019
2022	Iridium oxide nanoparticles	Macromolecule-based system	Cancer, Nervous disorders	Suppresses tumor growth, in vivo studies	Assa et al., 2017

4. Latest Approaches Used in Drug Delivery Systems for Several Diseases

4.1 Hypertension and Cardiovascular Diseases (CVDs)

Cardiovascular diseases (CVDs) are the leading cause of death globally, accounting for nearly 17.9 million deaths each year, according to the World Health Organization. A major contributor to this alarming statistic is hypertension, commonly referred to as high blood pressure. Hypertension is not limited to a specific age, gender, or demographic; it affects approximately 1.13 billion individuals globally, as reported in 2015 (Yadav BK et al., 2019). It exerts its deleterious effects by damaging critical organs such as the heart, kidneys, eyes, and brain, ultimately leading to various CVDs including atherosclerosis, myocardial infarction, ischemic heart disease, congestive heart failure, and stroke. The standard pharmacological treatment of hypertension includes diuretics, ACE inhibitors, beta-blockers, and calcium channel blockers. However, these often require lifelong adherence and may cause adverse side effects or reduced efficacy due to patient-specific variations. In response, complementary and alternative medicine (CAM) has gained attention. Over 95% of hypertensive patients reportedly benefit from CAM, which includes Traditional Chinese Medicine (TCM) practices such as acupuncture and herbal therapy. Clinical studies have confirmed that acupuncture can help normalize circadian rhythms and lower blood pressure in hypertensive individuals (Xiong X et al., 2013). These integrative approaches present a holistic avenue alongside conventional therapies.

4.2 Nanoparticles as Drug Delivery Agents in the Treatment of CVDs

Nanotechnology has opened new frontiers in the treatment of cardiovascular disorders. Among the various nanocarriers, gold nanoparticles (AuNPs) are particularly prominent due to their biocompatibility, ease of functionalization, low toxicity, and high surface area (Ali et al.,

2023). Gold nanoparticles enhance the delivery of cardioprotective agents, ensuring targeted and efficient drug accumulation at the site of myocardial injury or inflammation. For instance, the clinically approved drug Simdax (levosimendan), when conjugated with gold nanoparticles, demonstrated superior therapeutic potential in rats with doxorubicin-induced heart failure, showing enhanced retention in the injured tissue and improved cardiac function (Spivak et al., 2013). In addition to gold nanoparticles, lipid-based nanoparticles, polymeric nanoparticles, and dendrimers are being engineered to encapsulate antihypertensive drugs for controlled and sustained release, thus reducing dosing frequency and side effects (Mazhar et al., 2023). Nanoparticles also hold potential in facilitating gene therapy for hypertension, delivering siRNA or CRISPR components to silence pathogenic genes associated with blood pressure regulation (Zafar et al., 2023).

4.3 Nanoparticle-Based Drug Delivery in Parkinson's Disease

Parkinson's disease (PD) is a progressive neurodegenerative disorder primarily characterized by the depletion of dopamine (DA) in the brain. Conventional dopamine replacement therapies, although effective in the early stages, suffer from limitations due to poor permeability across the blood-brain barrier (BBB), leading to suboptimal bioavailability and systemic side effects such as nausea, hypotension, and dyskinesia (Garbayo, E et al., 2013). Nano drug delivery systems have been developed to overcome these challenges. Chitosan-based nanoparticles have shown promise in facilitating the translocation of dopamine across the BBB. In preclinical studies, dopamine-loaded chitosan nanoparticles not only demonstrated biocompatibility but also enhanced dopamine levels in a dose-dependent manner, reducing cytotoxic effects (Trapani, A et al., 2011). Furthermore, innovative strategies like intracranial implantation of dopamine-loaded cellulose acetate phthalate nanoparticles have enabled sustained release over extended periods. A study reported dopamine entrapment efficiency of 63% with peak levels occurring by day three post-implantation and a steady release lasting up to 30 days (Pillay, S et al., 2009). These advancements provide a platform for non-invasive, efficient, and long-term management of Parkinson's disease.

4.4 Drug Delivery Approaches in Blood Diseases

Blood disorders—including anemia, leukemia, hemophilia, thalassemia, and platelet abnormalities—require precision medicine strategies to minimise side effects and maximise therapeutic outcomes. Traditional treatments such as bone marrow transplants and chemotherapy

are associated with high costs, invasive procedures, and systemic toxicity. Nanoparticles offer a paradigm shift in the treatment of hematologic conditions as detail in **Figure 2**. For example, siRNA-coated nanocomposites have shown inhibitory effects on tumor cells in leukemia models, representing a non-invasive, gene-silencing therapeutic modality (Gonzalez-Valdivieso, J et al., 2021). In thalassemia, iron overload is managed using chelating agents, such as deferoxamine, which can be delivered more efficiently and with reduced side effects using nanoparticle-based formulations. In hemophilia and clotting disorders, nanomedicine is being explored to deliver clotting factors or regulate coagulation pathways. These nanosystems are designed for site-specific delivery, improved half-life, and minimal immune response.

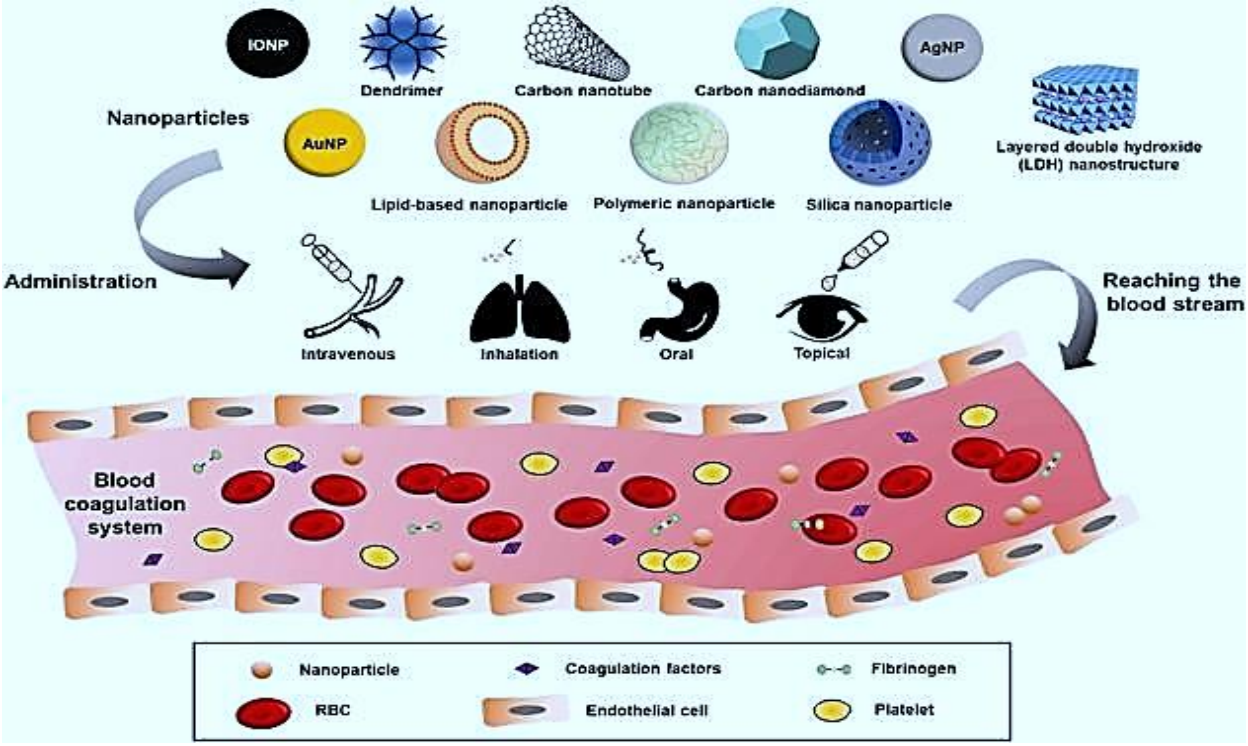


Figure 2: Mechanism of nanoparticles through the blood coagulation system (Parasd et al., 2018).

4.5 Nanoparticle-Based Strategies for Thrombosis

Thrombosis, or the formation of blood clots within blood vessels, is a critical component of many cardiovascular pathologies, including myocardial infarction, deep vein thrombosis, and pulmonary embolism. Traditional diagnostic techniques, such as Doppler ultrasound, CT angiography, and MRI, can localize thrombi but fall short in providing compositional and temporal

details of the clots (Falati, S et al., 2002). Nanotechnology has introduced advanced tools for both the diagnosis and treatment of thrombosis. Nanoparticles functionalized with fibrin-targeting ligands or coagulation factor-specific markers enable high-resolution imaging of clot structure and age. For example, radiolabeled nanoparticles with fibrin ligands enable accurate and non-invasive visualization of clots (Tung, C-H et al., 2003). Iron oxide nanoworms (NWs), conjugated with thrombin-activatable peptides (TAPs), have demonstrated exceptional selectivity and binding affinity to thrombin, a key enzyme in the clot formation process. This targeted approach not only enhances diagnostic accuracy but also facilitates the delivery of thrombus-specific therapies (Su, M et al., 2022).

4.6 Risk Exposure to Nanoparticles

Despite their tremendous potential, nanoparticles are not without risks. Their size, surface charge, and composition can result in unpredictable biological interactions. Nanoparticles smaller than 10 nm can penetrate cellular membranes and accumulate in various organs, raising concerns about neurotoxicity, immunogenicity, and cytotoxicity (Thomas, S.W et al., 2007; Huang, Q et al., 2010). Neurological conditions such as Parkinson's disease and Alzheimer's disease have been associated with chronic exposure to specific metal oxide nanoparticles. Dermatological conditions, such as urticaria and dermatitis, are also noted due to immune activation triggered by nanoparticle contact. The toxicity of nanoparticles is highly dependent on dose, exposure duration, and physicochemical properties, warranting extensive preclinical and clinical safety evaluations before therapeutic deployment.

Conclusion

Nanoparticles represent a transformative innovation in drug delivery systems due to their customizable physical, chemical, and biological properties. By leveraging the nanoscale dimensions and modifiable surfaces of their engineered nanocarriers, researchers have developed a diverse range of nanocarriers—including spherical nanoparticles, core-shell structures, nanorods, nanowires, hollow spheres, and mesoporous nanoparticles—for disease-specific drug delivery applications. This review highlights the evolving role of nanotechnology in targeting complex diseases such as cardiovascular disorders, neurodegenerative conditions like Parkinson's, blood malignancies, and coagulation disorders. Furthermore, the integration of nanomedicine with traditional treatment modalities and advanced diagnostics signifies a new era in personalized and precision medicine. Nonetheless, the growing body of evidence regarding nanoparticle-associated

toxicity necessitates a balanced approach—maximising therapeutic gain while minimizing risk exposure. Future research should focus on biocompatibility, regulatory frameworks, and real-time tracking systems to fully harness the potential of nanoparticles in clinical practice.

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