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NANOTECHNOLOGY-BASED DRUG DELIVERY FOR PRECISION AND PERSONALIZED MEDICINE

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Abstract:

Nanotechnology has emerged as an important platform for improving the delivery, targeting, and therapeutic performance of conventional and advanced medicines. Nanocarriers can modify the pharmacokinetic and biodistribution profiles of therapeutic agents, improve solubility and stability, facilitate transport across biological barriers, and enable controlled or stimulus-responsive drug release. These properties are particularly relevant to precision medicine, where treatment is tailored according to disease characteristics, molecular biomarkers, genetic information, and patient-specific responses. Nanoparticles can be engineered by modifying their size, surface charge, composition, architecture, targeting ligands, and responsiveness to biological stimuli. Major nanocarrier systems include liposomes, lipid nanoparticles, polymeric nanoparticles, polymeric micelles, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers, nanocrystals, inorganic nanoparticles, and hybrid nanocarriers. Their applications extend from cancer therapy and gene delivery to RNA therapeutics, neurological disorders, infectious diseases, and theranostics. Recent advances in artificial intelligence, biomarker-guided targeting, and multifunctional nanocarriers are further supporting the development of personalized nanomedicine. However, biological barriers, toxicity, immunogenicity, manufacturing complexity, scale-up, reproducibility, and regulatory requirements continue to limit clinical translation. Overall, nanotechnology provides a flexible platform for developing more selective, controlled, and patient-specific therapeutic strategies.

Keywords: *Nanotechnology, nanocarriers, targeted drug delivery, precision medicine, personalized medicine, lipid nanoparticles, gene delivery, RNA therapeutics, theranostics.*

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INTRODUCTION:

Nanotechnology has emerged as a transformative approach in modern pharmaceutical sciences, providing opportunities to improve drug solubility, stability, bioavailability, pharmacokinetics, biodistribution, and therapeutic efficacy.[1] Nanocarriers generally possess dimensions in the nanometer range and can be engineered with specific physicochemical characteristics to transport therapeutic agents to desired biological sites.[2] Unlike conventional drug-delivery systems, nanocarriers can be designed to protect the drug during circulation, facilitate cellular uptake, control drug release, and modify the distribution of therapeutic molecules.[3]

Precision medicine aims to provide therapeutic interventions according to the molecular, genetic, physiological, and pathological characteristics of individual patients.[4] Nanotechnology is particularly suitable for precision medicine because nanocarriers can be customized with different materials, surface ligands, therapeutic payloads, and stimulus-responsive properties.[5] Such flexibility enables the development of delivery systems capable of addressing disease heterogeneity and patient-to-patient variation.[6]

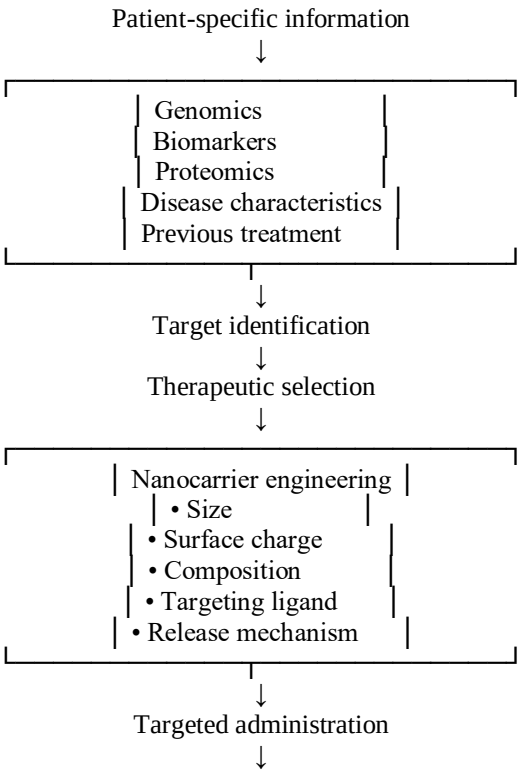
The integration of nanotechnology with molecular diagnostics, genomics, proteomics, artificial intelligence, and biomarker identification has resulted in the emergence of precision nanomedicine **and** personalized nanomedicine.[7] These approaches seek not only to deliver a drug to the correct site but also to select an appropriate therapeutic agent and delivery system according to individual disease characteristics.

Concept of Precision and Personalized Nanomedicine

Precision medicine involves identifying specific biological characteristics associated with a disease and using this information to select an appropriate therapeutic strategy.[8] Personalized medicine extends this approach by considering individual patient characteristics, including genetic background, biomarkers, disease phenotype, drug response, and clinical history.[9]

Nanotechnology can contribute to these approaches at several levels. First, nanoparticles can improve the delivery of poorly soluble or unstable therapeutic molecules. Second, surface modification can facilitate tissue- or cell-specific targeting. Third, nanocarriers can provide controlled or stimuli-responsive drug release. Finally, nanoparticles can simultaneously transport therapeutic and diagnostic components, resulting in theranostic systems.[10] The Conceptual pathway of precision nanomedicine were showed in Figure 1.

Figure 1. Conceptual pathway of precision nanomedicine



Controlled release
↓
Therapeutic response
↓
Treatment monitoring
↓
Therapy optimization

Major Nanocarriers for Precision Drug Delivery

A wide range of nanocarriers have been investigated for precision drug delivery, including liposomes, lipid nanoparticles, polymeric nanoparticles, polymeric micelles, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers, nanocrystals, inorganic nanoparticles, and hybrid systems.[11] The selection of a particular nanocarrier depends on the physicochemical characteristics of the drug, intended route of administration, target tissue, release requirements, and desired therapeutic effect.[12] The Major Nanocarriers for Precision Drug Delivery were showed in Table 1.

Liposomes

Liposomes are spherical vesicular systems composed primarily of phospholipid bilayers surrounding an aqueous core.[13] Hydrophilic drug can be incorporated within the aqueous compartment, whereas hydrophobic molecules can be incorporated within the lipid bilayer.[14] Surface modification with polyethylene glycol can improve circulation characteristics, while antibodies, peptides, aptamers, or small molecules can provide active targeting.[15]

Liposomes have therefore become important carriers for anticancer agents, antimicrobial drugs, proteins, peptides, and nucleic acids.[16] Their ability to accommodate both hydrophilic and lipophilic molecules makes them versatile pharmaceutical delivery systems. The structure of liposomes were showed in Figure 2.

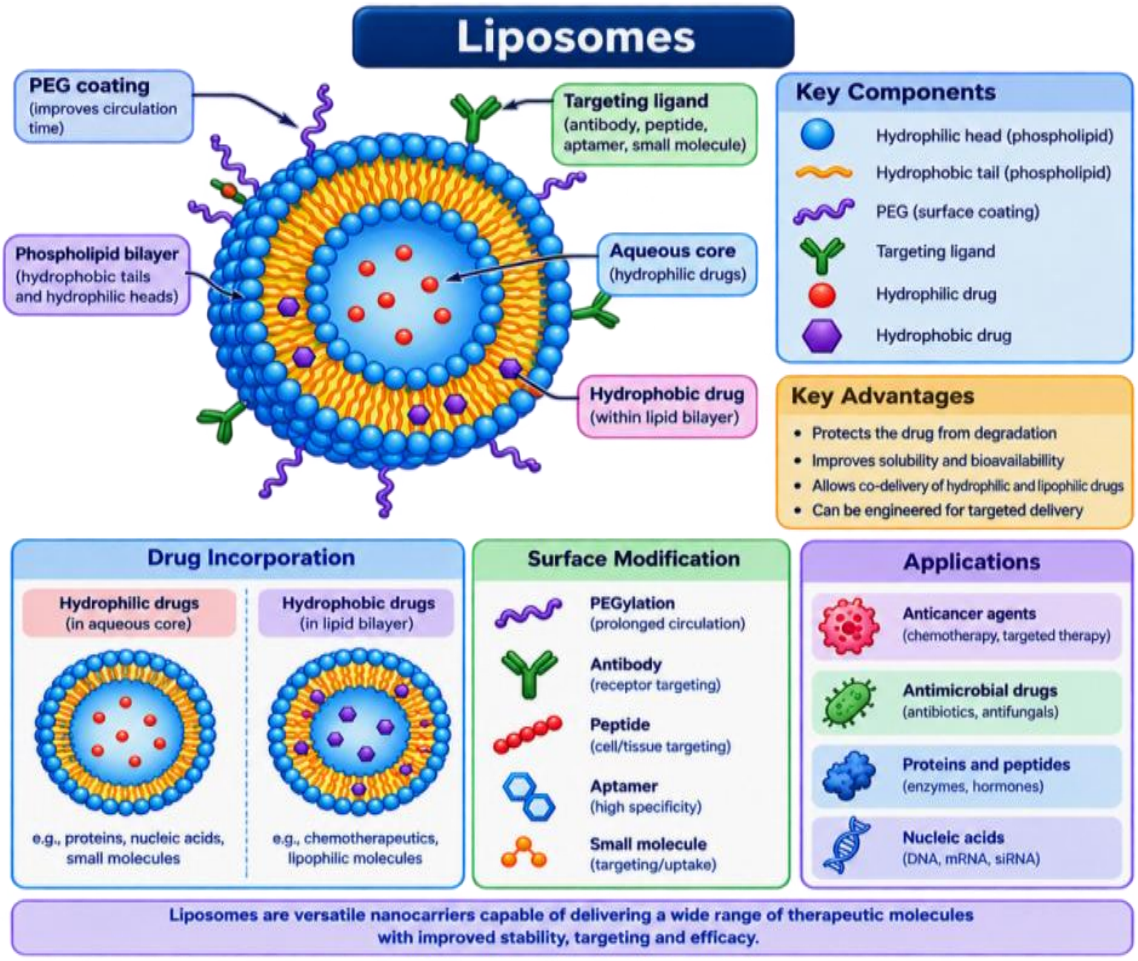


Figure 2. Structure of Liposomes

Lipid Nanoparticles

Lipid nanoparticles (LNPs) have gained considerable importance in the delivery of nucleic acids.[17] they generally contain ionizable lipids together with helper lipids, cholesterol, and a surface-stabilizing lipid component.[18] LNPs can encapsulate RNA molecules and protect them against degradation during systemic transport.[19]

The successful application of lipid nanoparticles in mRNA-based therapeutics has established their importance as a platform for advanced drug delivery.[20] Current research is directed toward improving organ-specific delivery, cellular targeting, endosomal escape, and therapeutic selectivity.[21] The Structure of Lipid Nanoparticles were showed in Figure 3.

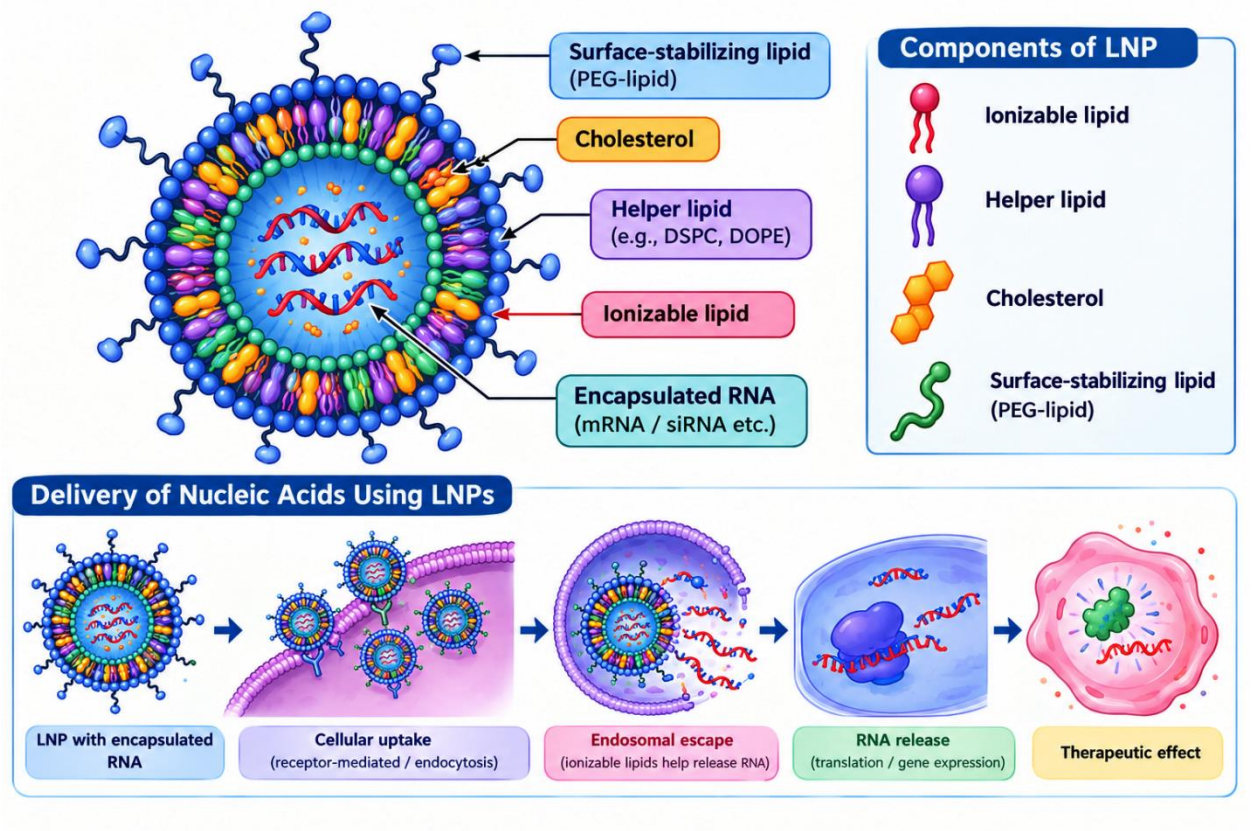


Figure 3. Structure of Lipid Nanoparticles

Polymeric Nanoparticles

Polymeric nanoparticles can be prepared from biodegradable polymers such as poly(lactic-co-glycolic acid), polylactic acid, and related materials.[22] They can provide sustained drug release through diffusion, polymer degradation, or a combination of mechanisms.[23] Surface modification can further improve circulation, targeting, and cellular uptake.

Polymeric Micelles

Polymeric micelles consist of amphiphilic polymers that self-assemble into structures containing a hydrophobic core and hydrophilic outer shell.[24] They are particularly useful for improving the apparent solubility and systemic delivery of poorly water-soluble drugs.[25]

Solid Lipid Nanoparticles and Nanostructured Lipid Carriers

Solid lipid nanoparticles (SLNs) consist of a solid lipid matrix capable of incorporating therapeutic molecules.[26] Nanostructured lipid carriers (NLCs) incorporate both solid and liquid lipids and can provide improved drug loading compared with some conventional lipid systems.[27]

Dendrimers

Dendrimers are highly branched, nanoscale macromolecules with numerous terminal functional groups.[28] Their well-defined architecture allows drugs, targeting ligands, imaging agents, or nucleic acids to be incorporated or attached to the structure.[29]

Nanocrystals

Drug nanocrystals consist primarily of crystalline drug particles stabilized by suitable surfactants or polymers.[30] Reduction of particle size produces a substantial increase in surface area and can enhance the dissolution rate of poorly water-soluble drugs.[31]

Table 1. Major nanocarriers and their applications

Nanocarrier	Principal characteristic	Potential application
Liposomes	Phospholipid bilayer	Targeted drug delivery
Lipid nanoparticles	Efficient nucleic-acid encapsulation	mRNA and siRNA delivery
Polymeric nanoparticles	Biodegradable matrix	Controlled drug release
Polymeric micelles	Hydrophobic core	Poorly soluble drugs
SLNs	Solid lipid matrix	Controlled delivery
NLCs	Solid + liquid lipid matrix	Improved drug loading
Dendrimers	Branched architecture	Drug/gene delivery
Nanocrystals	High surface area	Solubility enhancement
Inorganic nanoparticles	Magnetic/optical properties	Imaging and therapy
Hybrid nanoparticles	Multiple materials/functions	Multifunctional therapy

Targeted Drug Delivery

Targeted drug delivery is a major component of precision nanomedicine. The objective is to increase drug concentration at the site of disease while reducing exposure to healthy tissues.[32] Targeting can be broadly classified into passive and active targeting.

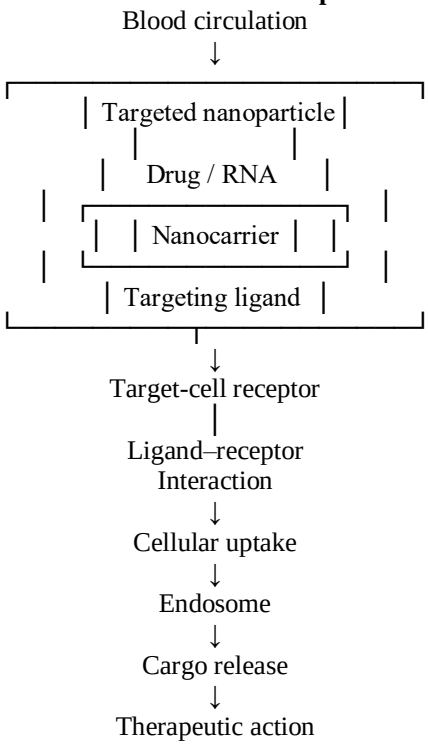
Passive Targeting

Passive targeting exploits physiological differences between diseased and healthy tissues. In cancer, the enhanced permeability and retention (EPR) effect has been extensively investigated as a mechanism for nanoparticle accumulation in tumor tissues.[33] However, the EPR effect is highly variable and depends on tumor type, vascular characteristics, stromal composition, tumor size, and patient-specific factors.[34] Therefore, relying exclusively on passive targeting may not provide consistent therapeutic outcomes.

Active Targeting

Active targeting involves modifying the surface of nanoparticles with molecules that recognize receptors or biomarkers expressed on target cells.[35] Targeting ligands include monoclonal antibodies, antibody fragments, peptides, aptamers, carbohydrates, and small molecules.[36] Ligand–receptor interactions can promote cellular binding and receptor-mediated endocytosis, potentially increasing intracellular delivery.[37] The mechanism of active nanoparticle targeting were showed in Figure 4.

Figure 4. Mechanism of active nanoparticle targeting



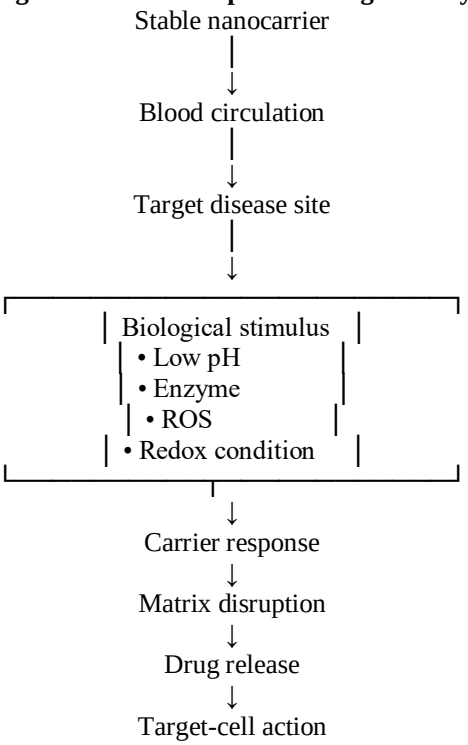
Stimuli-Responsive Nanocarriers

Stimuli-responsive nanocarriers are designed to release their therapeutic cargo in response to specific endogenous or exogenous stimuli.[38] Endogenous stimuli include pH, enzymes, redox conditions, reactive oxygen species, and disease-

associated metabolites.[39] External stimuli include light, ultrasound, magnetic fields, and temperature.[40]

For example, pH-sensitive nanoparticles can remain relatively stable in physiological circulation but undergo structural changes in acidic tumor or intracellular environments.[41] similarly, enzyme-responsive systems can be designed to release drugs in tissues exhibiting increased expression of specific enzymes.[42] The Stimuli-responsive drug delivery were showed in Figure 5.

Figure 5. Stimuli-responsive drug delivery



Nanotechnology in Cancer Precision Medicine

Cancer represents one of the most important areas of precision nanomedicine. Tumors exhibit substantial heterogeneity in molecular characteristics, receptor expression, vascularity, extracellular matrix composition, and drug sensitivity.[43]

Nanocarriers can improve the pharmacokinetic profile of anticancer agents and provide opportunities for targeted delivery.[44] They can also facilitate combination therapy by simultaneously transporting two or more therapeutic agents.[45]

Potential therapeutic combinations include:

- Chemotherapeutic drug + siRNA
- Chemotherapeutic drug + immunomodulator
- Small-molecule inhibitor + nucleic acid
- Drug + imaging agent
- Multiple anticancer drugs

The development of targeted nanoparticles based on tumor-specific biomarkers represents an important strategy for addressing interpatient and intratumoral heterogeneity.[46]

Nanotechnology for Gene and RNA Delivery

Nucleic-acid therapeutics have significant therapeutic potential but face major delivery challenges. Free RNA is susceptible to enzymatic degradation and generally has limited ability to cross cellular membranes.[47] The Nanoparticle-mediated RNA delivery were showed in Figure 6.

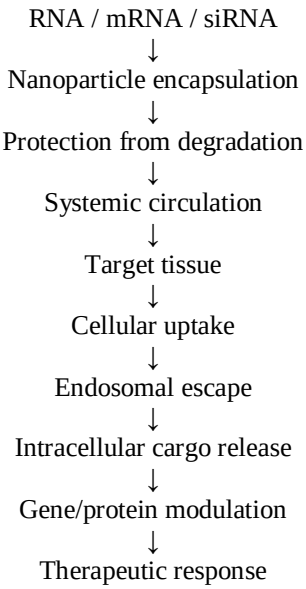
Nanocarriers can protect nucleic acids from degradation, facilitate cellular uptake, and promote intracellular release.[48] Lipid nanoparticles have become particularly important for mRNA and siRNA delivery.[49]

Nanotechnology is also being explored for the delivery of:

- mRNA
- siRNA
- miRNA
- DNA
- antisense oligonucleotides
- CRISPR-associated components
- Gene-editing systems

The efficiency of RNA delivery depends on overcoming sequential biological barriers, including systemic stability, tissue distribution, cellular uptake, endosomal escape, and intracellular release.[50]

Figure 6. Nanoparticle-mediated RNA delivery

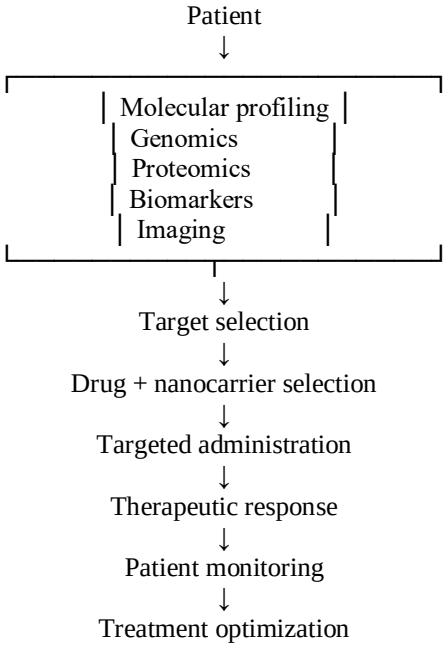


Personalized Nanomedicine

Personalized nanomedicine involves tailoring therapeutic delivery according to individual patient characteristics.[51] These characteristics may include genetic profile, disease subtype, receptor expression, biomarkers, previous treatment history, pharmacokinetic behavior, and treatment response. The Personalized nanomedicine workflow were showed in Figure 7.

A personalized nanocarrier may therefore differ between patient groups with different molecular characteristics.[52] For example, patients exhibiting a specific receptor on tumor cells could potentially be considered for nanoparticles functionalized with a ligand recognizing that receptor.

Figure 7. Personalized nanomedicine workflow



Theranostic Nanoparticles

Theranostics combines diagnosis and therapy within a single platform.[53] Nanoparticles can be designed to carry therapeutic agents together with imaging or diagnostic components.[54]

A theranostic system may provide information regarding disease localization, drug delivery, treatment response, and disease progression.[55] Imaging components can include fluorescent molecules, magnetic nanoparticles, radionuclides, or other imaging probes.

The integration of therapy and diagnosis may therefore support treatment monitoring and facilitate treatment adjustment according to individual therapeutic responses.

Nanotechnology for Central Nervous System Delivery

The blood–brain barrier (BBB) represents a major obstacle to the delivery of many therapeutic agents to the central nervous system.[56] Nanocarriers have been investigated as platforms for improving the transport of drugs, genes, proteins, and other therapeutic molecules across or around BBB-related barriers.[57]

Surface functionalization with ligands capable of interacting with receptors involved in receptor-mediated transcytosis has been investigated as one strategy.[58] Intranasal nanocarrier systems have also attracted attention because they may provide alternative pathways for transporting therapeutic molecules toward the brain.[59]

Potential applications include:

- Alzheimer's disease
- Parkinson's disease
- Brain tumors
- Ischemic stroke
- Neuroinflammation
- Gene therapy

Nanotechnology in Infectious Diseases

Nanotechnology has also been investigated for targeted delivery of antimicrobial agents.[60] Nanocarriers can improve drug solubility, protect unstable molecules, facilitate tissue penetration, and potentially increase drug accumulation at infection sites.[61]

Nanoparticles may also be engineered to carry antimicrobial drugs together with targeting ligands or imaging agents. This approach could be particularly useful for intracellular infections where conventional drugs have limited access to infected cells.

Role of Artificial Intelligence in Nanomedicine

Artificial intelligence (AI) and machine learning are emerging as important tools for nanomedicine development. Nanoparticle formulation involves numerous interacting variables, including particle size, polydispersity, surface charge, lipid/polymer composition, drug loading, encapsulation efficiency, and release characteristics.[62]

AI models can potentially assist in:

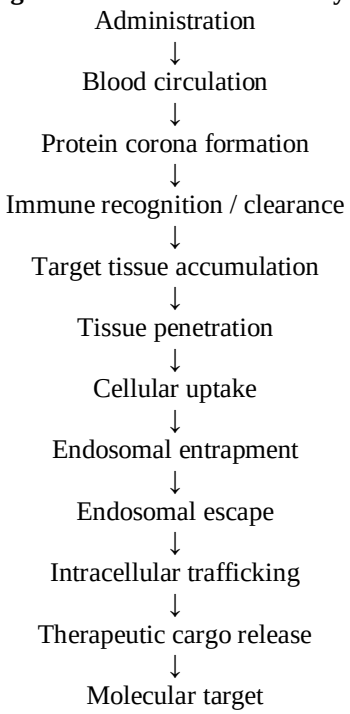
- Nanoparticle formulation optimization
- Prediction of physicochemical properties
- Prediction of drug loading
- Prediction of drug release
- Identification of suitable targeting ligands
- Prediction of biodistribution
- Patient stratification
- Analysis of multi-omics data

The integration of AI with nanotechnology may accelerate the identification of optimized formulations and facilitate the development of patient-specific therapeutic systems.[63]

Biological Barriers to Nanomedicine

Nanoparticles must overcome several biological barriers before reaching their intended intracellular target. These include protein corona formation, immune recognition, renal clearance, uptake by the mononuclear phagocyte system, vascular barriers, extracellular matrix, cellular membranes, endosomal entrapment, and intracellular trafficking.[64] The Biological barriers encountered by nanoparticles were showed in Figure 8.

Figure 8. Biological barriers encountered by nanoparticles



The biological behavior of nanoparticles depends strongly on their size, morphology, surface chemistry, charge, composition, and interactions with biological proteins.[65] These parameters can also influence their pharmacokinetics, biodistribution, cellular uptake, and toxicity.

Advantages of Nanotechnology-Based Precision Drug Delivery

Nanotechnology offers several potential advantages for precision and personalized medicine:

1. Enhancement of drug solubility.
2. Improvement of bioavailability.
3. Protection of unstable therapeutic molecules.
4. Controlled and sustained drug release.
5. Targeted drug delivery.
6. Improved intracellular delivery.
7. Delivery of nucleic acids and proteins.
8. Reduction of unwanted systemic exposure.
9. Possibility of combination therapy.
10. Integration of diagnosis and therapy.
11. Potential for patient-specific therapeutic design.
12. Compatibility with biomarker-guided treatment strategies.

Challenges and Limitations

Despite significant advances, several challenges continue to limit the clinical translation of nanomedicine. Nanoparticle toxicity and immunogenicity require comprehensive evaluation because physicochemical properties can influence biological interactions.[66] Manufacturing and scale-up are also challenging because small changes in formulation composition or processing conditions can affect particle size, surface properties, drug loading, and release behavior.[67]

Additional challenges include:

- Biological variability between patients
- Tumor heterogeneity
- Limited tissue penetration
- Protein corona formation
- Immunological clearance
- Long-term toxicity
- Reproducibility
- Manufacturing scale-up
- High development costs
- Regulatory complexity

The translation of nanomedicines from laboratory research to clinical products therefore requires integrated consideration of formulation science, pharmacology, toxicology, manufacturing, and regulatory requirements.[68]

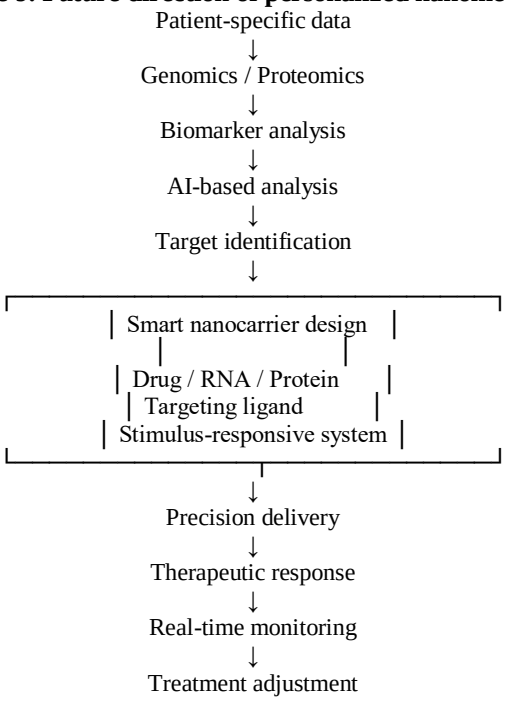
Future Perspectives

Future developments in precision nanomedicine are likely to involve integration of nanotechnology with genomics, proteomics, molecular diagnostics, artificial intelligence, gene editing, and real-time therapeutic monitoring.[69]

Smart nanocarriers may increasingly incorporate multiple functions, including targeting, controlled release, imaging, and therapeutic monitoring.[70] Biomarker-guided nanoparticle design may help identify patients who are more likely to respond to a particular nanomedicine.

AI-assisted formulation design may further accelerate the development of personalized delivery systems by integrating large datasets containing formulation, biological, pharmacokinetic, and patient-response information.[71]

Figure 9. Future direction of personalized nanomedicine



CONCLUSION:

Nanotechnology-based drug delivery represents an important technological foundation for precision and personalized medicine. Nanocarriers can improve the solubility, stability, pharmacokinetic behavior, biodistribution, and controlled release of therapeutic agents. Their surfaces can be engineered with targeting ligands, while their internal structures can be designed for controlled or stimulus-responsive release.

The application of nanotechnology to cancer therapy, RNA delivery, gene therapy, neurological disorders, infectious diseases, and theranostics demonstrates its broad therapeutic potential. The emergence of lipid nanoparticles for nucleic-acid delivery has further demonstrated the clinical relevance of nanoscale drug-delivery technologies.

The future of nanomedicine is expected to move beyond conventional drug encapsulation toward patient-specific, biomarker-guided, multifunctional and intelligent delivery systems**.** Integration with artificial intelligence, molecular diagnostics, genomics, and real-time monitoring may provide increasingly individualized therapeutic strategies. Nevertheless, biological variability, toxicity, manufacturing, scalability, reproducibility, and regulatory challenges must be systematically addressed to achieve broader clinical translation. Nanotechnology therefore represents not merely a drug-delivery technology but a potential platform for integrating diagnosis, targeted therapy, controlled release, and personalized treatment within a single therapeutic framework.

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