Natural Resources for Human Health

eISSN: 2583-1194

Original Research

Received 18 May 2026
Revised 25 June 2026
Accepted 10 July 2026

Natural Resources for Human Health 2026, Vol. 6 (12s): 338–357

KEYWORDS:
Biomarker-guided therapy, Targeted nanomedicine, Precision medicine, Nanocarriers, Targeted drug delivery, Theranostics.

Biomarker-Guided Targeted Nanomedicine

Dheyauldeen Ali Smran[1], P. Shailaja[2]

[1]Student, Department of Pharmaceutics, AU College of Pharmaceutical Sciences, Andhra University, Visakhapatnam, India
[2]Associate Professor, Department of Pharmaceutics, AU College of Pharmaceutical Sciences, Andhra University, Visakhapatnam, India
Corresponding Author E-mail: Dheya.ali98@gmail.com
[2]E-mail: dr.pshailaja@andhrauniversity.edu.in

ABSTRACT: Nanomedicine has emerged as a powerful approach for improving the diagnosis and treatment of complex diseases by utilizing nanoscale drug delivery systems. Conventional therapeutic methods often suffer from limitations such as poor solubility, non-specific distribution, rapid systemic clearance, and associated toxicity. Nanocarrier-based systems address these challenges by enhancing drug stability, improving pharmacokinetic behavior, and enabling controlled and site-specific delivery of therapeutic agents. In recent years, the integration of biomarkers with nanotechnology has significantly advanced targeted therapeutic strategies and contributed to the evolution of precision medicine (2,3,4). Biomarkers, including proteins, genes, enzymes, and metabolites, serve as measurable indicators of physiological and pathological conditions and play a crucial role in disease diagnosis, prognosis, and therapeutic response (11,12,13). Biomarker-guided targeted nanomedicine involves engineering nanoparticles capable of selectively recognizing and interacting with biomarker-expressing cells or tissues. Functionalization of nanocarriers with ligands such as antibodies, peptides, or small molecules allows precise drug delivery to diseased sites, thereby enhancing therapeutic efficacy while minimizing off-target effects. This approach has demonstrated considerable potential, particularly in cancer therapy, where biomarkers such as HER2, EGFR, and VEGF are widely utilized for targeted drug delivery(59,60,61). Furthermore, emerging applications in cardiovascular, neurological, and infectious diseases highlight the broader clinical relevance of this strategy. However, challenges such as biomarker heterogeneity, nanoparticle safety, large-scale manufacturing, and regulatory issues remain to be addressed. Continued interdisciplinary research is essential to optimize biomarker identification, nanocarrier design, and clinical translation, ultimately enabling more effective and personalized therapeutic interventions (38,39,76).

INTRODUCTION

Conventional drug delivery systems, including oral, intravenous, and intramuscular routes, have been widely used in clinical practice; however, they suffer from several limitations that reduce therapeutic efficiency(6,9,41). One of the major drawbacks is the non-specific distribution of drugs throughout the body, which results in significant exposure of healthy tissues and leads to adverse effects and toxicity. In addition, many drugs exhibit poor bioavailability due to low solubility or extensive first-pass metabolism. Rapid drug clearance from systemic circulation further reduces drug concentration at the target site, often requiring repeated or higher doses, which negatively impacts patient compliance. Moreover, biological barriers such as the blood–brain barrier limit the effectiveness of many drugs, particularly in treating neurological disorders. These challenges highlight the need for more advanced and efficient drug delivery strategies.

Nanomedicine has emerged as a promising solution to overcome these limitations by applying nanotechnology in medical applications such as drug delivery, diagnostics, and imaging(2,3,4,27). Nanoparticles, typically ranging from 1 to 100 nm, possess unique properties including high surface area, tunable surface characteristics, and improved reactivity. These features enable them to encapsulate drugs, protect them from degradation, and release them in a controlled manner. Various nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, dendrimers, and metallic nanoparticles have been developed to enhance drug solubility, prolong circulation time, and improve cellular uptake. As a result, nanomedicine offers significant advantages over conventional drug delivery systems(9,25).

Targeted drug delivery systems further enhance therapeutic outcomes by delivering drugs specifically to diseased tissues, cells, or molecular targets. This approach minimizes drug exposure to healthy tissues and reduces systemic toxicity. Targeting can occur through passive mechanisms, such as the enhanced permeability and retention (EPR) effect in tumors, or active mechanisms involving ligand-receptor interactions(8,21,44). In active targeting, nanocarriers are functionalized with molecules such as antibodies, peptides, or aptamers that selectively bind to specific cellular markers, ensuring precise drug delivery.

Biomarkers play a crucial role in this context as measurable indicators of physiological or pathological conditions. They include proteins, nucleic acids, enzymes, and metabolites that can be detected in biological samples. Biomarkers are essential for early disease diagnosis, monitoring disease progression, and evaluating therapeutic responses. Furthermore, predictive biomarkers help in selecting appropriate therapies, forming the basis of personalized medicine(11,12,13).

Biomarker-guided targeted nanomedicine integrates biomarker identification with nanotechnology-based delivery systems. In this approach, nanoparticles are engineered to recognize specific biomarkers expressed on diseased cells, allowing precise drug delivery. This strategy enhances drug accumulation at target sites, improves therapeutic efficacy, and minimizes side effects. It is particularly effective in cancer therapy, where tumor-specific biomarkers can be exploited for selective treatment (14,15).

This review aims to provide an overview of biomarker-guided targeted nanomedicine, including its principles, nanocarrier systems, and mechanisms of targeting. It also discusses recent advancements, clinical applications, challenges, and future perspectives, emphasizing its potential in developing precise and patient-specific therapeutic strategies.

BIOMARKERS IN PRECISION MEDICINE

Biomarkers play a crucial role in the advancement of precision medicine by enabling the identification of disease-specific molecular characteristics and guiding individualized therapeutic strategies. Precision medicine aims to tailor medical treatment according to the genetic, molecular, and physiological profile of each patient. In this context, biomarkers serve as measurable biological indicators that provide valuable insights into disease mechanisms, progression, and treatment responses. They can be detected in biological samples such as blood, tissues, urine, or other body fluids and may include genes, proteins, metabolites, or molecular signatures. The integration of biomarkers into clinical practice allows healthcare professionals to diagnose diseases earlier, predict patient outcomes, and select the most appropriate treatment strategies. With advances in molecular biology, genomics, and bioinformatics, the identification and validation of novel biomarkers have significantly improved the development of targeted therapies and personalized treatment approaches(11,12,13,47).

DEFINITION AND CLASSIFICATION OF BIOMARKERS

A biomarker is defined as a measurable biological characteristic that reflects normal physiological processes, pathological conditions, or responses to therapeutic interventions. Biomarkers are widely used in biomedical research and clinical practice to improve disease detection, guide therapeutic decisions, and monitor treatment effectiveness. Based on their clinical applications, biomarkers are generally classified into several categories.

Diagnostic biomarkers are used to identify the presence or absence of a disease. These biomarkers help detect diseases at an early stage, often before clinical symptoms become apparent. Early diagnosis enables timely treatment and improves patient outcomes. For example, certain proteins or genetic mutations can serve as diagnostic markers for various cancers and metabolic disorders.

Prognostic biomarkers provide information about the likely course or progression of a disease. These biomarkers help clinicians predict disease severity, progression, and potential complications. Prognostic biomarkers are particularly useful in conditions such as cancer, where they can indicate the likelihood of disease recurrence or metastasis.

Predictive biomarkers are used to determine the probability of a patient responding to a specific therapeutic intervention. These biomarkers help clinicians select the most effective treatment for individual patients and avoid therapies that may not produce beneficial outcomes. Predictive biomarkers are essential in personalized medicine because they enable targeted therapies based on the molecular characteristics of the disease.

Pharmacodynamic biomarkers are indicators that reflect the biological response of a patient to a drug or therapeutic intervention. These biomarkers are often used in clinical trials and treatment monitoring to evaluate the effectiveness of a therapy and determine whether the drug is producing the intended biological effect(48,49).

Table 1. Major types of biomarkers and their clinical applications in disease diagnosis and therapeutic decision-making(11,12,13,48).

Biomarker Type	**Description**	**Example Biomarkers**	**Clinical Application**
Diagnostic biomarkers	Indicators used to detect the presence of a disease	PSA, CA-125, Troponin	Early disease detection and diagnosis
Prognostic biomarkers	Biomarkers that predict disease progression or outcome	Ki-67, BRCA mutations	Estimating disease severity and survival probability
Predictive biomarkers	Biomarkers that predict patient response to a specific therapy	HER2, EGFR	Selection of targeted therapies
Pharmacodynamic biomarkers	Indicators reflecting the biological response to treatment	Cytokine levels, tumor markers	Monitoring treatment effectiveness
Monitoring biomarkers	Used to evaluate disease progression or recurrence	Circulating tumor DNA (ctDNA)	Tracking disease progression

MOLECULAR BASIS OF BIOMARKERS

Biomarkers originate from various molecular components of the body, including genetic material, proteins, metabolites, and epigenetic modifications. Advances in molecular biology and omics technologies have significantly expanded the understanding of the molecular basis of biomarkers and their role in disease diagnosis and treatment.

Genetic biomarkers are based on variations in DNA sequences that may influence disease susceptibility, progression, or treatment response. These biomarkers include gene mutations, single nucleotide polymorphisms (SNPs), and gene expression profiles. Genetic biomarkers are widely used in the diagnosis of inherited diseases and in identifying patients who may benefit from targeted therapies.

Proteomic biomarkers are proteins or protein expression patterns that are associated with specific disease states. Proteins perform essential biological functions and often reflect physiological changes occurring within the body. Alterations in protein expression, structure, or activity can indicate the presence of disease or changes in disease progression. Proteomic biomarkers are commonly used in cancer diagnosis and monitoring

Metabolomic biomarkers are small molecules produced during metabolic processes within cells and tissues. Changes in metabolic pathways can lead to variations in the concentration of certain metabolites, which can serve as indicators of disease or physiological changes. Metabolomic biomarkers are increasingly used to study metabolic disorders, cardiovascular diseases, and cancer.

Epigenetic biomarkers involve modifications that regulate gene expression without altering the underlying DNA sequence. These modifications include DNA methylation, histone modification, and non-coding RNA regulation. Epigenetic changes can influence gene activity and play a significant role in the development of diseases such as cancer and neurological disorders. Epigenetic biomarkers are particularly valuable for understanding disease mechanisms and identifying new therapeutic targets(13,47,48).

CLINICAL IMPORTANCE OF BIOMARKERS

Biomarkers have become essential tools in modern clinical practice because they provide valuable information for disease detection, treatment selection, and monitoring therapeutic responses. Their integration into healthcare systems has significantly improved the ability to manage complex diseases and develop personalized treatment strategies.

One of the most important applications of biomarkers is early disease detection. Early identification of diseases enables timely medical intervention, which can prevent disease progression and improve survival rates. Many diseases, including cancer and cardiovascular disorders, can be detected at an early stage through specific molecular biomarkers.

Another important clinical application is patient stratification, which involves grouping patients based on their molecular or genetic characteristics. This approach allows clinicians to identify subgroups of patients who are more likely to benefit from certain treatments. Patient stratification is a key component of precision medicine because it ensures that therapies are tailored to the specific needs of individual patients.

Biomarkers are also valuable for monitoring therapeutic response. By measuring changes in biomarker levels during treatment, clinicians can determine whether a therapy is effective or whether modifications to the treatment plan are necessary. Monitoring biomarkers helps in evaluating drug efficacy, detecting treatment resistance, and assessing potential disease recurrence.

Overall, the incorporation of biomarkers into clinical practice has significantly enhanced the ability to diagnose diseases accurately, guide therapeutic decisions, and improve patient outcomes. As research in molecular biology and nanotechnology continues to advance, biomarkers are expected to play an even more important role in the development of targeted and personalized therapeutic approaches.

FUNDAMENTALS OF TARGETED NANOMEDICINE

Targeted nanomedicine is an advanced therapeutic approach that combines nanotechnology with targeted drug delivery strategies to improve the precision and effectiveness of medical treatments. It involves the use of nanoscale carriers engineered to transport therapeutic agents directly to diseased tissues or cells. These nanocarriers can be designed to recognize specific biological targets such as receptors, enzymes, or molecular biomarkers present on diseased cells. By directing drugs specifically to the site of disease, targeted nanomedicine minimizes exposure to healthy tissues and enhances the therapeutic index of drugs. The development of targeted nanomedicine has been driven by advancements in materials science, molecular biology, and pharmaceutical technology, which have enabled the fabrication of nanoparticles with tailored size, shape, surface properties, and functionalization capabilities.

NANOMEDICINE IN DRUG DELIVERY

Nanomedicine in drug delivery refers to the application of nanoscale materials and technologies to improve the delivery of therapeutic agents within the body. Nanocarriers are typically engineered particles ranging from approximately 1 to 100 nanometers in size. At this scale, materials exhibit unique physical and chemical properties that differ significantly from their bulk counterparts. These properties allow nanoparticles to interact effectively with biological systems, penetrate tissues more efficiently, and deliver drugs in a controlled and targeted manner.

CONCEPT OF NANOSCALE DRUG CARRIERS

Nanoscale drug carriers are specially designed nanoparticles capable of encapsulating, adsorbing, or conjugating therapeutic molecules such as small drug molecules, proteins, peptides, nucleic acids, or imaging agents. These carriers act as protective vehicles that transport drugs through the biological environment while preventing premature degradation or inactivation. Once the nanocarriers reach the target site, they release the drug in a controlled fashion, ensuring that the therapeutic agent exerts its effect precisely where it is needed.

Nanocarriers can be engineered with surface modifications that enable them to interact selectively with specific cellular receptors or molecular targets. For instance, nanoparticles can be functionalized with antibodies, peptides, or ligands that recognize disease-specific biomarkers. This targeting capability allows nanocarriers to accumulate preferentially in diseased tissues, such as tumors or inflamed regions, thereby improving treatment efficiency. Additionally, nanoscale carriers can cross biological barriers that often limit the effectiveness of conventional drugs, including the blood–brain barrier.

ADVANTAGES OVER CONVENTIONAL FORMULATIONS

Compared with traditional pharmaceutical formulations, nanocarrier-based drug delivery systems provide several important advantages. One major benefit is the ability to improve the solubility and stability of poorly soluble drugs. Many therapeutic agents exhibit limited water solubility, which restricts their absorption and bioavailability. Encapsulation within nanocarriers can enhance drug solubility and facilitate efficient transport in biological fluids.

Nanomedicine also allows for sustained or controlled drug release, which maintains therapeutic drug concentrations over extended periods and reduces the need for frequent dosing. Furthermore, nanoparticles can protect sensitive drugs such as proteins and nucleic acids from enzymatic degradation in the body. By improving drug stability and targeting capability, nanocarrier systems significantly enhance therapeutic outcomes while minimizing unwanted side effects.

TYPES OF NANOCARRIERS

A variety of nanocarrier systems have been developed to improve targeted drug delivery, each offering unique structural features and functional benefits. The choice of nanocarrier depends on the drug's properties, target site, and required release pattern.

1. Liposomes

Liposomes are spherical vesicles composed of phospholipid bilayers enclosing an aqueous core. They can carry both hydrophilic drugs (in the core) and hydrophobic drugs (within the lipid bilayer), making them highly versatile. Due to their similarity to biological membranes, liposomes exhibit excellent biocompatibility and biodegradability. They can also be surface-modified with ligands for targeted delivery. Liposomal formulations are widely used in clinical applications, especially in cancer therapy(16).

2. Polymeric Nanoparticles

Polymeric nanoparticles are prepared from biodegradable polymers such as PLA, PLGA, and chitosan. Drugs can either be encapsulated within the polymer matrix or attached to the surface. These carriers provide high stability, controlled drug release, and easy surface modification for targeting. Their degradation rate can be tailored, making them ideal for sustained and long-term drug delivery(17).

3. Solid Lipid Nanoparticles (SLNs)

SLNs are composed of solid lipids stabilized by surfactants and remain solid at body temperature. They are particularly suitable for lipophilic drugs and help enhance bioavailability. SLNs protect drugs from degradation and offer controlled release while maintaining good biocompatibility and low toxicity(18).

4. Dendrimers

Dendrimers are highly branched, tree-like macromolecules with a well-defined structure. Their multiple surface functional groups allow attachment of drugs and targeting ligands. They provide precise control over size and functionality, making them suitable for targeted drug delivery, gene therapy, and imaging applications(19).

5. Niosomes

Niosomes are vesicular carriers formed from non-ionic surfactants and cholesterol. Similar to liposomes, they can encapsulate both hydrophilic and hydrophobic drugs but offer greater stability and lower cost. Niosomes enhance drug penetration and are widely explored for controlled and targeted drug delivery(20).

6. Metallic Nanoparticles

Metallic nanoparticles, such as gold and silver nanoparticles, possess unique optical and electrical properties. Gold nanoparticles are especially useful in drug delivery, imaging, and cancer therapy due to their easy functionalization with biomolecules. They are also used in photothermal therapy and biosensing applications(50).

7. Carbon-Based Nanoparticles

Carbon-based nanomaterials, including carbon nanotubes, graphene oxide, and fullerenes, have high surface area and excellent mechanical properties. They can efficiently carry drugs and genetic material into cells. However, their clinical application requires careful evaluation of toxicity and safety(51,52).

Table 2. Common nanocarrier systems used in biomarker-guided targeted drug delivery(16–20,50–52)

Nanocarrier Type	Composition	Key Advantages	Example Applications
Liposomes	Phospholipid bilayer vesicles	Biocompatible, capable of carrying hydrophilic and hydrophobic drugs	Cancer chemotherapy delivery
Polymeric nanoparticles	Biodegradable polymers such as PLGA	Controlled drug release and improved stability	Targeted anticancer drug delivery
Solid lipid nanoparticles	Solid lipid core stabilized by surfactants	Enhanced drug stability and controlled release	Delivery of lipophilic drugs
Dendrimers	Highly branched synthetic macromolecules	High drug loading capacity and surface functionalization	Gene therapy and targeted drug delivery
Niosomes	Non-ionic surfactant vesicles	Cost-effective and stable vesicular carriers	Drug delivery in cancer and dermatology
Metallic nanoparticles	Gold, silver, or iron oxide nanoparticles	Useful for imaging and therapy	Photothermal therapy and diagnostics
Carbon-based nanoparticles	Graphene oxide, carbon nanotubes	Large surface area for drug loading	Drug delivery and biosensing

ADVANTAGES OF NANOMEDICINE

Nanomedicine offers several important advantages compared with conventional therapeutic approaches. These benefits have significantly contributed to the increasing interest in nanoparticle-based drug delivery systems.

1.Improved Bioavailability

Many drugs exhibit poor bioavailability due to low solubility, rapid metabolism, or limited absorption in the gastrointestinal tract. Nanoparticles can enhance drug solubility and improve absorption by increasing the surface area of the drug and facilitating transport across biological membranes. As a result, therapeutic drug levels can be achieved more effectively.

2.Controlled Drug Release

Nanocarriers can be engineered to release drugs in a controlled and sustained manner over a specific period of time. This controlled release mechanism helps maintain stable drug concentrations in the body, reducing the need for frequent dosing and improving patient compliance. Controlled release also prevents sudden spikes in drug concentration that could lead to toxicity.

3.Reduced Systemic Toxicity

One of the major advantages of targeted nanomedicine is the ability to reduce systemic toxicity. By directing drugs specifically to diseased tissues, nanocarriers minimize exposure to healthy organs and tissues. This targeted approach reduces adverse side effects and enhances the safety profile of therapeutic agents.

4.Enhanced Therapeutic Efficacy

Nanomedicine improves the therapeutic effectiveness of drugs by increasing drug accumulation at the target site and facilitating efficient cellular uptake. Nanoparticles can also overcome biological barriers that limit drug delivery, allowing drugs to reach previously inaccessible tissues. As a result, targeted nanomedicine can significantly improve treatment outcomes, particularly in diseases such as cancer, neurological disorders, and infectious diseases.

MECHANISMS OF TARGETING IN NANOMEDICINE

Targeting mechanisms are fundamental to the effectiveness of nanomedicine, as they determine how efficiently therapeutic nanoparticles reach and accumulate at the intended site of action. In conventional drug delivery, drugs are distributed non-specifically throughout the body, which often leads to reduced therapeutic efficiency and increased side effects. Nanomedicine overcomes these limitations by employing advanced targeting strategies that enhance drug accumulation at diseased tissues while minimizing exposure to healthy cells. These targeting mechanisms are broadly classified into passive targeting, active targeting, and stimuli-responsive targeting, each based on distinct biological and physicochemical principles .

1. Passive Targeting

Passive targeting is one of the earliest and most widely utilized approaches in nanomedicine. This strategy relies on the natural physiological characteristics of diseased tissues, particularly tumors and inflamed regions, to facilitate the preferential accumulation of nanoparticles. Unlike active targeting, passive targeting does not involve specific ligand-receptor interactions but instead exploits abnormalities in the vascular structure and lymphatic system.

Enhanced Permeability and Retention (EPR) Effect

The enhanced permeability and retention (EPR) effect is the primary mechanism underlying passive targeting. Tumor tissues typically exhibit abnormal, highly permeable blood vessels due to rapid and disorganized angiogenesis. These vessels contain large gaps between endothelial cells, allowing nanoparticles of appropriate size (typically 10–200 nm) to extravasate into the tumor interstitial space.

In addition to increased vascular permeability, tumors often have inefficient lymphatic drainage systems. This results in the retention of nanoparticles within the tumor microenvironment for extended periods. The combined effect of enhanced permeability and poor lymphatic clearance leads to the accumulation of nanoparticles specifically in tumor tissues.

Passive targeting offers several advantages, including simplicity and the ability to deliver drugs without the need for complex surface modifications. However, its effectiveness may vary depending on tumor type, size, and patient-specific factors. Some tumors exhibit limited vascular permeability, which can reduce nanoparticle accumulation. Despite these limitations, passive targeting remains a fundamental strategy in nanomedicine(8,21,44,45).

2. Active Targeting

Active targeting enhances the specificity of drug delivery by functionalizing nanoparticles with molecules that can recognize and bind to specific biomarkers expressed on diseased cells. These targeting molecules, known as ligands, enable selective interaction with receptors or antigens present on the cell surface. Upon binding, nanoparticles are typically internalized through receptor-mediated endocytosis, allowing direct intracellular drug delivery.

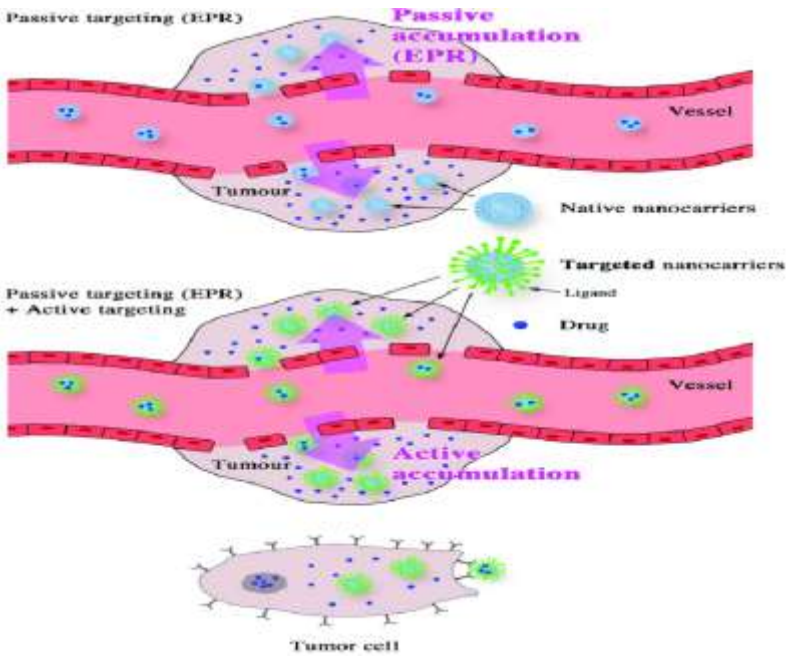

Figure 1: Schematic representation of passive (EPR effect) and active targeting mechanisms in nanomedicine. Passive targeting enables nanoparticle accumulation in tumor tissues due to enhanced vascular permeability, whereas active targeting involves ligand-functionalized nanocarriers that bind specifically to receptors on tumor cells, enhancing cellular uptake and therapeutic efficiency(8,21,23,54).

Ligand–Receptor Mediated Targeting

This is the most widely used active targeting strategy. Nanoparticles are conjugated with ligands such as folic acid, transferrin, or growth factors that bind to overexpressed receptors on diseased cells. For example, folate receptors and epidermal growth factor receptors are commonly overexpressed in cancer cells. Binding of the ligand to the receptor facilitates nanoparticle uptake into the cell, increasing drug concentration at the target site.

Antibody-Mediated Targeting

Antibody-mediated targeting utilizes monoclonal antibodies or antibody fragments that specifically bind to antigens present on diseased cells. This approach offers high specificity and strong binding affinity, making it highly effective in targeting cancer cells. Once bound, the nanoparticle-antibody complex is internalized, enabling localized drug release. However, antibody-based systems may increase production complexity, cost, and the risk of immune reactions.

Peptide-Based Targeting

Peptides are short amino acid sequences that serve as efficient targeting ligands. Compared to antibodies, peptides are smaller, less immunogenic, and easier to synthesize. They can be designed to target specific receptors involved in disease processes such as tumor angiogenesis or inflammation. Peptide-functionalized nanoparticles exhibit improved tissue penetration and are widely used in targeted drug delivery and diagnostic applications.

Overall, active targeting significantly improves drug specificity, enhances cellular uptake, and reduces off-target effects compared to passive targeting(23,54).

Stimuli-Responsive Targeting

Stimuli-responsive nanomedicine represents an advanced targeting strategy in which nanoparticles are engineered to release drugs in response to specific internal or external stimuli. This approach provides controlled and site-specific drug release, further improving therapeutic precision.

pH-Responsive Systems

pH-responsive nanoparticles exploit the acidic microenvironment of tumors and inflamed tissues. While normal tissues have a physiological pH of approximately 7.4, tumor environments are slightly acidic (pH 6.5–6.9), and intracellular compartments such as endosomes are even more acidic. pH-sensitive nanocarriers remain stable under normal conditions but release drugs in acidic environments through structural changes such as polymer degradation or bond cleavage.

Temperature-Responsive Systems

Temperature-responsive nanocarriers release drugs in response to elevated temperatures. Tumor tissues often exhibit slightly higher temperatures than normal tissues, and external heating techniques such as hyperthermia can be used to trigger drug release. Temperature-sensitive polymers undergo phase transitions at specific temperatures, enabling controlled drug delivery.

Enzyme-Responsive Systems

Enzyme-responsive nanocarriers utilize enzymes that are overexpressed in diseased tissues, such as matrix metalloproteinases and proteases. These nanoparticles contain enzyme-sensitive linkers or coatings that degrade in the presence of specific enzymes, triggering drug release at the target site.

Redox-Responsive Systems

Redox-responsive systems take advantage of the difference in redox conditions between healthy and diseased cells. Cancer cells often have high intracellular concentrations of reducing agents such as glutathione. Nanoparticles designed with redox-sensitive bonds, such as disulfide linkages, remain stable in circulation but release drugs upon entering the reducing intracellular environment(37,56,57,58).

Biomarker-Guided Targeted Nanomedicine

Biomarker-guided targeted nanomedicine represents a significant advancement in modern drug delivery and precision medicine. It integrates the identification of disease-specific biomarkers with advanced nanocarrier systems to achieve highly selective drug delivery. In many diseases, particularly cancer, specific molecules such as receptors, enzymes, or proteins are overexpressed or uniquely present on diseased cells. These molecules act as biomarkers that can be selectively recognized by engineered nanoparticles. By targeting these biomarkers, therapeutic agents can be delivered directly to diseased cells while minimizing exposure to healthy tissues, thereby reducing systemic toxicity and improving treatment outcomes.

The combination of biomarkers with nanotechnology has greatly enhanced the specificity and efficiency of targeted therapies. Nanoparticles can be functionalized with ligands such as antibodies, peptides, aptamers, or small molecules that bind specifically to disease-associated biomarkers. Upon binding, the nanoparticle is internalized into the target cell, where it releases the drug at the desired site of action. This targeted delivery approach increases drug accumulation at the disease site and significantly improves therapeutic efficacy, making it a key component of precision medicine.

CONCEPT AND PRINCIPLES

Integration of Biomarkers with Nanomedicine

The concept of biomarker-guided nanomedicine is based on the integration of molecular diagnostics with nanoparticle-based drug delivery systems. Biomarkers provide critical information about disease characteristics, including receptor expression, genetic mutations, and altered cellular pathways. These molecular signatures serve as targets for nanoparticle-based therapies.

In this approach, nanoparticles are designed to specifically recognize and bind to disease-associated biomarkers through surface modification with targeting ligands such as antibodies, peptides, aptamers, or small molecules. Once bound to the biomarker, nanoparticles are internalized via receptor-mediated endocytosis, allowing intracellular delivery of the therapeutic agent. This strategy enables highly selective drug delivery and enhances treatment precision.

Additionally, this integration supports the concept of theranostics, where nanoparticles carry both therapeutic agents and imaging components. This allows simultaneous diagnosis, treatment, and real-time monitoring of therapeutic responses, improving clinical decision-making.

Personalized Therapeutic Strategies

A major advantage of biomarker-guided nanomedicine is its ability to support personalized therapeutic strategies. Unlike conventional treatments that follow a generalized approach, biomarker-based strategies consider the molecular variability among patients.

By analyzing patient-specific biomarkers, clinicians can design or select nanomedicine systems tailored to individual disease profiles. This ensures that therapeutic agents are delivered specifically to affected cells, thereby improving efficacy and minimizing adverse effects.

Personalized nanotherapy enhances treatment outcomes by increasing drug effectiveness and reducing unnecessary exposure to ineffective therapies. Thus, biomarker-guided nanomedicine plays a crucial role in advancing precision medicine, aiming to deliver the right treatment to the right patient at the right time.

Biomarker-Targeted Nanocarriers

Biomarker-targeted nanocarriers are nanoparticles engineered to recognize specific molecular markers expressed on diseased cells. These nanocarriers can be designed to deliver drugs, genes, or imaging agents selectively to cells expressing the targeted biomarker. Several biomarker-targeted nanocarrier systems have been developed for disease treatment, particularly in oncology.

HER2-Targeted Nanoparticles

Human epidermal growth factor receptor 2 (HER2) is a transmembrane protein that plays an important role in regulating cell growth and proliferation. Overexpression of the HER2 receptor is commonly observed in certain types of breast cancer and is associated with aggressive tumor growth and poor prognosis. Because of its high expression in tumor cells, HER2 has become an important biomarker for targeted therapy.

Nanoparticles designed to target HER2 are typically functionalized with antibodies or antibody fragments that recognize the HER2 receptor. These nanoparticles bind selectively to HER2-expressing cancer cells and facilitate the delivery of anticancer drugs directly to the tumor site. HER2-targeted nanocarriers have demonstrated improved therapeutic efficacy and reduced systemic toxicity compared with conventional chemotherapy(59).

EGFR-Targeted Nanocarriers

Epidermal growth factor receptor (EGFR) is another important biomarker that is frequently overexpressed in several types of cancers, including lung cancer, colorectal cancer, and head and neck cancers. EGFR plays a key role in regulating cell proliferation, survival, and differentiation. Abnormal activation of this receptor can contribute to tumor growth and metastasis.

Nanocarriers targeting EGFR are typically modified with ligands such as antibodies or peptides that bind specifically to the receptor. Once the nanoparticle binds to EGFR on the cancer cell surface, it can be internalized through receptor-mediated endocytosis. This process allows the drug-loaded nanoparticle to release its therapeutic payload within the cancer cell, thereby enhancing treatment effectiveness(60).

PSMA-Targeted Nanoparticles

Prostate-specific membrane antigen (PSMA) is a cell surface protein that is highly expressed in prostate cancer cells. Because of its selective expression in prostate tumors, PSMA has become a valuable biomarker for targeted drug delivery and diagnostic imaging.

Nanoparticles designed to target PSMA are often functionalized with ligands or antibodies that specifically recognize this biomarker. These targeted nanocarriers can deliver anticancer drugs directly to prostate tumor cells while minimizing exposure to surrounding healthy tissues. PSMA-targeted nanomedicine has shown promising results in both therapeutic and imaging applications(28,48).

VEGF-Targeted Nanomedicine

Vascular endothelial growth factor (VEGF) is a signaling protein involved in the formation of new blood vessels, a process known as angiogenesis. Many tumors rely on angiogenesis to obtain nutrients and oxygen necessary for their growth and survival. VEGF is therefore considered an important biomarker associated with tumor progression.

Nanomedicine systems targeting VEGF aim to inhibit tumor angiogenesis by delivering anti-angiogenic drugs directly to the tumor microenvironment. These nanoparticles may carry therapeutic agents that block VEGF signaling pathways, thereby preventing the formation of new blood vessels and restricting tumor growth. VEGF-targeted nanomedicine has been investigated as a promising strategy for controlling tumor progression and improving cancer treatment outcomes(61).

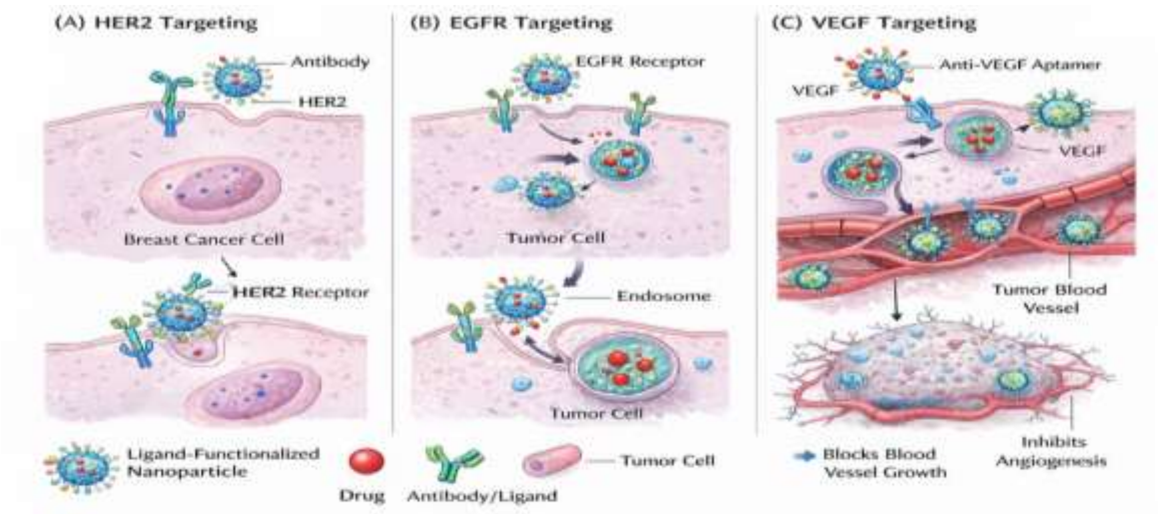

Figure2: Schematic representation of biomarker-targeted nanomedicine illustrating ligand-functionalized nanoparticles selectively binding to overexpressed biomarkers such as HER2, EGFR, and VEGF. HER2-targeted nanoparticles enable selective delivery to breast cancer cells, EGFR-targeted systems facilitate receptor-mediated endocytosis in tumor cells, and VEGF-targeted nanocarriers inhibit tumor angiogenesis by blocking blood vessel formation(59,60,61).

Table 3. Representative biomarkers and their corresponding nanomedicine targeting strategies in cancer therapy(28,48,59–61).

Biomarker	Disease	Nanomedicine Strategy
HER2	Breast cancer	Antibody-conjugated nanoparticles
EGFR	Lung cancer	Ligand-modified nanoparticles
PSMA	Prostate cancer	Targeted liposomal delivery
VEGF	Tumor angiogenesis	Anti-angiogenic nanocarriers

Natural Resources for Human Health
eISSN: 2583-1194

ROLE OF NANOTECHNOLOGY IN PRECISION THERAPY

Targeted Delivery to Biomarker-Expressing Cells

Nanotechnology enables the development of highly sophisticated drug delivery systems capable of recognizing specific biomarkers expressed on diseased cells. By attaching targeting ligands to the nanoparticle surface, nanocarriers can selectively bind to these biomarkers and deliver therapeutic agents directly to the affected cells. This targeted delivery mechanism improves drug localization at the disease site and enhances treatment effectiveness.

Improved Therapeutic Index

The therapeutic index of a drug represents the balance between its beneficial effects and its potential toxicity. Nanotechnology can significantly improve the therapeutic index by increasing drug accumulation at the target site while reducing systemic exposure. Targeted nanoparticles deliver drugs more efficiently to diseased tissues, allowing lower drug doses to achieve the desired therapeutic effect.

Reduced Off-Target Toxicity

One of the major challenges in conventional chemotherapy and other systemic treatments is the occurrence of severe side effects caused by drug exposure to healthy tissues. Biomarker-guided nanomedicine addresses this problem by directing therapeutic agents specifically to diseased cells. As a result, healthy tissues receive minimal drug exposure, which reduces toxicity and improves patient safety.

APPLICATIONS OF BIOMARKER-GUIDED NANOMEDICINE

Biomarker-guided nanomedicine has significantly advanced modern therapeutics by enabling highly specific and efficient drug delivery. By identifying disease-associated biomarkers and engineering nanoparticles to recognize these markers, drugs can be delivered directly to affected tissues while minimizing damage to healthy cells. This approach enhances therapeutic efficacy, reduces systemic toxicity, and improves overall patient outcomes. Biomarker-guided nanomedicine has shown promising applications across multiple disease areas, including cancer, cardiovascular disorders, neurological diseases, and infectious conditions .

1. Cancer Therapy

Cancer represents one of the most extensively explored areas in biomarker-guided nanomedicine. Tumor cells often overexpress specific molecular markers such as receptors, enzymes, and proteins, which serve as targets for selective drug delivery.

Tumor Biomarker Targeting

Tumor-associated biomarkers such as epidermal growth factor receptor (EGFR), human epidermal growth factor receptor 2 (HER2), folate receptor, vascular endothelial growth factor (VEGF), and prostate-specific membrane antigen (PSMA) play key roles in tumor progression, angiogenesis, and metastasis. Nanoparticles functionalized with ligands like antibodies or peptides can selectively bind to these biomarkers. Following binding, nanoparticles enter cells via receptor-mediated endocytosis, enabling precise drug delivery and reducing toxicity to normal tissues. This approach also promotes higher drug accumulation within the tumor microenvironment.

Nanoparticle-Mediated Chemotherapy

Nanoparticle-based chemotherapy involves encapsulating chemotherapeutic drugs within nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and solid lipid nanoparticles. These systems enhance drug stability, prevent premature degradation, and enable controlled drug release at the tumor site. Passive targeting through the enhanced permeability and retention (EPR) effect further improves drug accumulation, resulting in better therapeutic outcomes and fewer side effects compared to conventional chemotherapy.

Immunotherapy and Gene Therapy

Nanoparticles are increasingly used to deliver immunotherapeutic agents such as cytokines, immune checkpoint inhibitors, and tumor antigens. By targeting tumor-specific biomarkers, they enhance immune activation against cancer cells while minimizing systemic immune toxicity. In gene therapy, nanoparticles deliver nucleic acids such as DNA, mRNA, or siRNA to regulate gene expression and inhibit oncogenes. Biomarker-guided targeting ensures precise delivery, improving treatment effectiveness(28,29).

2. Cardiovascular Diseases

Cardiovascular diseases remain a major cause of mortality worldwide. Biomarker-guided nanomedicine offers innovative strategies for both diagnosis and treatment by targeting molecular markers associated with inflammation and plaque formation.

Targeting Inflammatory Biomarkers

Inflammatory biomarkers such as cytokines, adhesion molecules, and inflammatory proteins are highly expressed in conditions like atherosclerosis and myocardial infarction. Nanoparticles can be engineered to recognize these markers and deliver anti-inflammatory drugs directly to affected tissues. This targeted approach reduces vascular inflammation and limits systemic side effects. Additionally, nanoparticles carrying imaging agents can enable early detection of inflammation.

Nanocarriers for Atherosclerosis Treatment

Atherosclerosis involves plaque formation due to lipid accumulation and inflammation in arterial walls. Biomarkers such as oxidized low-density lipoproteins and macrophage markers can be targeted using nanocarriers. These systems can deliver cholesterol-lowering drugs, anti-inflammatory agents, or plaque-stabilizing compounds directly to plaques, improving treatment efficacy and preventing complications such as plaque rupture(30,64,65).

3. Neurological Disorders

Neurological disorders such as Alzheimer's disease, Parkinson's disease, and brain tumors present challenges due to the blood–brain barrier (BBB), which restricts drug entry into the brain.

Biomarker-Guided Delivery Across the Blood–Brain Barrier

Biomarker-guided nanomedicine enables drug delivery across the BBB by targeting specific receptors such as transferrin or insulin receptors on endothelial cells. Nanoparticles functionalized with ligands can undergo receptor-mediated transport across the BBB and release drugs within brain tissues. This strategy improves drug penetration and is particularly useful in treating neurodegenerative diseases by targeting amyloid plaques or neuroinflammatory pathways(31,62,63).

4. Infectious Diseases

Biomarker-guided nanomedicine has also demonstrated potential in treating infectious diseases by targeting pathogen-specific or infection-associated biomarkers.

Targeted Antimicrobial Nanotherapy

Nanoparticles can deliver antibiotics, antiviral, or antifungal agents directly to infected sites by recognizing specific biomarkers. This targeted delivery enhances drug concentration at the infection site, improves therapeutic effectiveness, and reduces the risk of drug resistance. Additionally, nanoparticles can enhance drug stability and bioavailability, while some exhibit intrinsic antimicrobial properties. This approach is being explored for treating bacterial, viral, and emerging infectious diseases(32,66,67).

DIAGNOSTIC APPLICATIONS OF BIOMARKER-GUIDED NANOMEDICINE (THERANOSTICS)

The integration of diagnostic and therapeutic functions within a single nanoscale platform has led to the emergence of theranostics, an advanced approach that combines disease detection, monitoring, and treatment. Biomarker-guided theranostic nanomedicine enables simultaneous identification of disease-specific markers, visualization of disease progression, and targeted drug delivery. This strategy is particularly valuable in precision medicine, as it allows coordinated and personalized treatment based on individual patient profiles.

Nanoparticles are highly suitable for theranostic applications due to their small size, large surface area, and ability to be functionalized with multiple components such as therapeutic agents, imaging probes, targeting ligands, and diagnostic molecules. By interacting specifically with disease-associated biomarkers, these multifunctional systems provide real-time information about disease status while simultaneously delivering therapy.

1. Nanoparticles for Biomarker Detection

Nanoparticles serve as highly sensitive tools for detecting disease-associated biomarkers, which are essential for early diagnosis, disease monitoring, and evaluation of therapeutic responses. Conventional diagnostic methods often lack sufficient sensitivity to detect biomarkers at low concentrations; however, nanoparticles overcome this limitation due to their enhanced physicochemical properties.

Various nanoparticles, including gold nanoparticles, magnetic nanoparticles, quantum dots, and silica nanoparticles, have been widely explored for biomarker detection. These particles can be functionalized with biomolecules such as antibodies, aptamers, peptides, or nucleic acids that specifically bind to target biomarkers. Upon binding, they generate detectable signals such as fluorescence, colorimetric changes, magnetic responses, or electrical signals.

Gold nanoparticles are commonly used in colorimetric assays due to their unique optical properties, while magnetic nanoparticles are valuable in biosensing and magnetic resonance imaging. Quantum dots provide highly sensitive fluorescence-based detection. Nanoparticle-based biosensors can detect proteins, nucleic acids, enzymes, and metabolites with high sensitivity and rapid response, making them highly suitable for point-of-care diagnostics and personalized medicine.

2. Imaging-Guided Therapy

Imaging-guided therapy is a key application of biomarker-guided nanomedicine, where nanoparticles function as contrast agents to visualize diseased tissues and guide treatment. These nanoparticles can be engineered to carry imaging agents compatible with modalities such as magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), optical imaging, and ultrasound.

Magnetic nanoparticles, particularly iron oxide nanoparticles, enhance contrast in MRI, while gold nanoparticles are effective in CT imaging due to their strong X-ray absorption. Fluorescent nanoparticles and quantum dots are widely used in optical imaging.

In this approach, nanoparticles are designed to accumulate selectively at disease sites by targeting specific biomarkers. Once localized, imaging techniques enable real-time monitoring of nanoparticle distribution and therapeutic delivery. This allows clinicians to evaluate treatment effectiveness and adjust therapeutic strategies accordingly. Imaging-guided therapy is especially beneficial in cancer treatment, where accurate tumor localization and monitoring are essential.

3. Combined Diagnosis and Treatment (Theranostics)

Theranostics represents a multifunctional approach in which a single nanoparticle system performs diagnostic and therapeutic functions simultaneously. These systems typically include a targeting ligand for biomarker recognition, a therapeutic agent for treatment, and an imaging probe for visualization.

This integrated approach allows clinicians to diagnose diseases, deliver targeted therapy, and monitor treatment responses in real time. One of the major advantages of theranostic nanomedicine is its ability to support personalized treatment strategies. By continuously monitoring biomarker expression and therapeutic outcomes, treatments can be adjusted according to patient-specific needs.

Theranostic nanomedicine has shown significant promise in cancer management, where nanoparticles carrying both imaging agents and anticancer drugs can selectively target tumor cells. This enables early detection, precise drug delivery, and continuous monitoring of therapeutic response. Beyond oncology, theranostic approaches are also being explored for cardiovascular and neurological disorders. Overall, this technology has the potential to revolutionize disease diagnosis and treatment by providing a comprehensive and patient-specific therapeutic platform(33,34,68,69).

RECENT ADVANCES IN BIOMARKER-GUIDED NANOMEDICINE

Recent progress in nanotechnology, molecular biology, and computational sciences has significantly expanded the scope of biomarker-guided nanomedicine. These advancements have enabled the development of more precise and efficient therapeutic systems capable of identifying disease-specific biomarkers, delivering drugs selectively, and monitoring treatment responses. Key innovations include artificial intelligence-based biomarker discovery, CRISPR-integrated nanomedicine, smart nanocarriers, and multifunctional nanoparticles.

1. AI-Based Biomarker Identification

Artificial intelligence (AI) has become a powerful tool for identifying disease-associated biomarkers. Machine learning and deep learning algorithms can analyze large and complex datasets generated from genomics, proteomics, metabolomics, and transcriptomics. These tools help identify molecular patterns such as gene mutations, protein expression profiles, and signaling pathways that serve as potential biomarkers.

AI also supports the design of targeted nanocarriers by predicting how nanoparticle properties influence drug delivery and therapeutic outcomes. Additionally, AI can predict patient responses to treatment, enabling the development of personalized therapeutic strategies and improving clinical decision-making(35,70,71).

2. CRISPR-Guided Nanomedicine

CRISPR technology has revolutionized gene editing by enabling precise modification of DNA sequences. When combined with nanocarriers, CRISPR systems can be efficiently delivered into target cells for therapeutic purposes. Nanoparticles protect CRISPR components, such as guide RNA and associated proteins, from degradation and facilitate their cellular uptake.

Biomarker-guided targeting enhances the precision of CRISPR delivery by ensuring that gene-editing tools reach only diseased cells. This approach can be used to correct genetic mutations, regulate gene expression, or suppress oncogenes in cancer cells. CRISPR-based nanomedicine shows strong potential in treating genetic disorders, cancers, and viral infections(36,72,73).

3. Smart Nanocarriers

Smart nanocarriers are advanced drug delivery systems designed to respond to specific biological or external stimuli. Unlike conventional systems, they release drugs only under certain conditions, such as changes in pH, enzyme activity, redox environment, temperature, or external signals like light and magnetic fields.

For example, pH-sensitive nanoparticles release drugs in the acidic tumor environment, while enzyme-responsive systems release drugs in the presence of disease-specific enzymes. This controlled release improves drug targeting, enhances therapeutic efficiency, and reduces systemic side effects, making smart nanocarriers a significant advancement in nanomedicine(37,57).

4. Multifunctional Nanoparticles

Multifunctional nanoparticles are designed to perform multiple roles within a single system, including drug delivery, imaging, biomarker detection, and therapeutic monitoring. These systems typically integrate targeting ligands, therapeutic agents, and imaging components.

Such nanoparticles enable simultaneous diagnosis and treatment (theranostics) and provide real-time feedback on treatment effectiveness. This allows clinicians to monitor nanoparticle distribution and adjust therapy as needed. Multifunctional nanoparticles have shown great promise in cancer therapy and are also being explored for cardiovascular, neurological, and infectious diseases(33,68).

CHALLENGES AND LIMITATIONS OF BIOMARKER-GUIDED NANOMEDICINE

Although biomarker-guided targeted nanomedicine has demonstrated significant potential in improving disease diagnosis and treatment, several scientific, technical, and regulatory challenges limit its widespread clinical application. The complexity of interactions between nanomaterials, biological systems, and therapeutic agents makes translation from laboratory research to clinical practice difficult. Key limitations include biomarker variability, nanoparticle toxicity, limited clinical translation, regulatory and manufacturing challenges, and high development costs

1. Biomarker Variability Among Patients

A major challenge is the variability in biomarker expression among patients. Factors such as genetic differences, environmental influences, disease stage, and immune responses contribute to this variability. In diseases like cancer, tumor heterogeneity further complicates targeting, as different cell populations may express different biomarkers or varying levels of the same biomarker. As a result, nanoparticles designed for a specific target may fail to reach all diseased cells.

Additionally, biomarker expression can change over time, especially during disease progression or in response to therapy, leading to treatment resistance. To address this issue, strategies such as multi-biomarker targeting, adaptable nanocarrier systems, and continuous biomarker monitoring are being explored.

2. Nanoparticle Toxicity Concerns

Nanoparticle toxicity remains a critical concern. Due to their small size and high surface reactivity, nanoparticles can interact strongly with biological systems, potentially causing oxidative stress, inflammation, or cellular damage. Some nanoparticles may accumulate in organs such as the liver, spleen, lungs, or kidneys, leading to long-term toxicity.

Factors such as particle size, shape, surface charge, and composition influence toxicity. While surface modifications can improve targeting and reduce adverse effects, they may also introduce additional complexity. Moreover, nanoparticles can trigger immune responses, leading to rapid clearance or inflammatory reactions. Therefore, extensive toxicological evaluation and careful design are essential.

3. Limited Clinical Translation

Despite promising preclinical results, only a limited number of nanomedicine therapies have reached clinical use. One major reason is the difference between experimental models and human biological systems. Results observed in cell cultures or animal models may not accurately reflect human responses.

Patient variability in metabolism, immune function, and disease characteristics further affects nanoparticle performance. Additionally, clinical trials required to evaluate safety and efficacy are time-consuming, expensive, and complex, slowing the transition from research to clinical application.

4. Regulatory and Manufacturing Challenges

Regulatory approval of nanomedicine is challenging due to the complexity of nanoparticle systems, which often include multiple components such as drugs, carriers, and targeting ligands. Each component can influence safety and therapeutic performance.

Standardized regulatory guidelines for nanomedicine are still evolving, which can delay approval processes. Manufacturing also presents challenges, as producing nanoparticles with consistent size, shape, and properties requires precise control. Scaling up production while maintaining quality and reproducibility remains a significant hurdle.

5. High Development Cost

The development of biomarker-guided nanomedicine is associated with high costs due to the need for advanced technologies, specialized materials, and multidisciplinary expertise. Extensive preclinical studies and multi-phase clinical trials further increase expenses.

Manufacturing and quality control processes are also more complex compared to conventional drugs, contributing to higher production costs. These financial challenges may limit accessibility and slow innovation. Collaborative efforts among academia, industry, and regulatory bodies are essential to support cost-effective development(38,39,74,75,76).

FUTURE PERSPECTIVES OF BIOMARKER-GUIDED NANOMEDICINE

Biomarker-guided nanomedicine has emerged as a powerful approach for improving the precision and effectiveness of modern therapies. Although significant progress has been made, further advancements are needed to fully realize its clinical potential. Future research is expected to focus on the integration of advanced technologies, improved biomarker discovery, personalized treatment strategies, and efficient clinical translation pathways .

1. Integration of Artificial Intelligence and Nanomedicine

Artificial intelligence (AI) is expected to play a major role in the future development of nanomedicine. Technologies such as machine learning and deep learning can analyze complex biological data, including genomic, proteomic, and metabolomic information, to identify new disease-related biomarkers.

AI can also assist in designing optimized nanoparticles by predicting how properties such as size, shape, and surface characteristics influence drug delivery and therapeutic outcomes. This helps in developing nanocarriers with improved targeting efficiency and reduced toxicity.

Additionally, AI can predict patient responses to therapies by analyzing clinical data, enabling more effective and personalized treatment selection. AI-based image analysis can further enhance diagnostic accuracy and allow real-time monitoring of disease progression when combined with nanoparticle imaging systems.

2. Development of Personalized Nanotherapeutics

Personalized medicine focuses on tailoring treatments based on individual patient characteristics. Biomarker-guided nanomedicine provides a strong platform for this approach by enabling targeted drug delivery based on specific molecular markers.

Future developments will involve designing nanocarriers that are customized according to the biomarker profile of each patient. Advances in genomic sequencing and molecular diagnostics will support this by identifying disease-specific genetic and protein signatures.

Another important direction is the development of modular nanocarrier systems that can be easily modified to target different biomarkers. Such adaptable systems will allow rapid customization of therapies, particularly for complex diseases like cancer, where variability between patients is high.

3. Advanced Biomarker Discovery Technologies

The effectiveness of biomarker-guided nanomedicine depends on the identification of reliable biomarkers. Advances in "omics" technologies—such as genomics, proteomics, metabolomics, and transcriptomics—have greatly improved biomarker discovery.

These technologies enable large-scale analysis of biological molecules, helping researchers understand disease mechanisms and identify specific molecular targets. Single-cell sequencing has further enhanced this field by allowing detailed analysis at the individual cell level, which is especially important in diseases like cancer

In addition, microfluidic systems and biosensors are emerging as powerful tools for rapid and sensitive biomarker detection. These technologies support early diagnosis and real-time monitoring of treatment responses.

4. Clinical Translation and Regulatory Considerations

Despite promising research outcomes, translating nanomedicine into clinical practice remains challenging. Key issues include safety evaluation, large-scale manufacturing, and regulatory approval.

Future efforts will focus on developing standardized methods for assessing the safety, biodistribution, toxicity, and therapeutic performance of nanoparticles. Advances in manufacturing techniques, such as microfluidic synthesis and automated production, will improve scalability and consistency.

Regulatory agencies are working to establish guidelines for nanomedicine; however, the complex nature of these systems requires specialized frameworks. Collaboration between researchers, industry, and regulatory bodies will be essential to ensure safe and efficient clinical translation.

CONCLUSION

Biomarker-guided targeted nanomedicine has emerged as a highly promising strategy for enhancing the precision and effectiveness of modern therapeutic approaches. The identification and application of disease-specific biomarkers have significantly improved early diagnosis and enabled the selective delivery of drugs to affected tissues. By integrating biomarker recognition with advanced nanocarrier systems, targeted drug delivery can be achieved, thereby minimizing exposure to healthy tissues and reducing systemic toxicity. This represents a substantial improvement over conventional drug delivery methods, which often lack specificity and are associated with undesirable side effects.

Furthermore, the incorporation of biomarkers into nanomedicine has accelerated the development of personalized therapeutic strategies. Since biomarker expression varies among individuals, analyzing patient-specific molecular profiles allows for the design of tailored treatment approaches. Nanoparticle-based delivery systems can be engineered to selectively interact with these biomarkers, ensuring precise delivery of therapeutic agents. This personalized approach enhances treatment efficacy while avoiding unnecessary exposure to ineffective therapies.

Biomarker-guided nanomedicine also plays a crucial role in advancing precision medicine through the development of theranostic platforms. These systems integrate diagnostic and therapeutic functions, enabling simultaneous disease detection, targeted drug delivery, and real-time monitoring of treatment responses. Such capabilities allow clinicians to make timely adjustments to therapeutic strategies, thereby improving disease management and patient outcomes.

Despite these advantages, several challenges remain in translating biomarker-guided nanomedicine into routine clinical practice. Key issues include variability in biomarker expression, concerns regarding nanoparticle safety, challenges in large-scale manufacturing, and the need for well-defined regulatory frameworks. Addressing these challenges will require extensive research and coordinated efforts among scientists, clinicians, and regulatory authorities.

Future progress in this field will depend on interdisciplinary collaboration across nanotechnology, molecular biology, bioinformatics, materials science, and artificial intelligence. Continued advancements in these areas will facilitate the discovery of novel biomarkers and the development of more efficient and safer nanocarrier systems. Overall, biomarker-guided nanomedicine holds great potential to revolutionize disease diagnosis and treatment, paving the way for more precise, effective, and patient-centered healthcare solutions(38,39,76).

REFERENCES

[1] Ferrari M. Cancer nanotechnology: opportunities and challenges. Nat Rev Cancer. 2005;5(3):161–71.
[2] Peer D, Karp JM, Hong S, Farokhzad OC, Margalit R, Langer R. Nanocarriers as an emerging platform for cancer therapy. Nat Nanotechnol. 2007;2(12):751–60.
[3] Shi J, Votruba AR, Farokhzad OC, Langer R. Nanotechnology in drug delivery and tissue engineering. Nat Rev Drug Discov. 2010;9(8):639–51.
[4] Farokhzad OC, Langer R. Impact of nanotechnology on drug delivery. ACS Nano. 2009;3(1):16–20.
[5] Torchilin VP. Multifunctional nanocarriers. Adv Drug Deliv Rev. 2012;64:302–15.
[6] Allen TM, Cullis PR. Drug delivery systems: entering the mainstream. Science. 2004;303(5665):1818–22.
[7] Duncan R. Polymer conjugates as anticancer nanomedicines. Nat Rev Cancer. 2006;6(9):688–701.
[8] Maeda H, Wu J, Sawa T, Matsumura Y, Hori K. Tumor vascular permeability and the EPR effect. J Control Release. 2000;65(1–2):271–84.
[9] Blanco E, Shen H, Ferrari M. Principles of nanoparticle design for overcoming biological barriers. Nat Biotechnol. 2015;33(9):941–51.
[10] Bae YH, Park K. Targeted drug delivery to tumors: myths and reality. J Control Release. 2011;153(3):198–205.
[11] Strimbu K, Tavel JA. What are biomarkers? Curr Opin HIV AIDS. 2010;5(6):463–6.
[12] Mayeux R. Biomarkers: potential uses and limitations. NeuroRx. 2004;1(2):182–8.
[13] Califf RM. Biomarker definitions and applications. Clin Pharmacol Ther. 2018;103(1):40–1.
[14] Ashley EA. The precision medicine initiative. JAMA. 2015;313(21):2119–20.
[15] Hamburg MA, Collins FS. The path to personalized medicine. N Engl J Med. 2010;363(4):301–4.
[16] Pattni BS, Chupin VV, Torchilin VP. New developments in liposomal drug delivery. Chem Rev. 2015;115(19):10938–66.
[17] Danhier F, Ansorena E, Silva JM, Coco R, Le Breton A, Préat V. PLGA nanoparticles. J Control Release. 2012;161(2):505–22.
[18] Müller RH, Radtke M, Wissing SA. Solid lipid nanoparticles. Adv Drug Deliv Rev. 2002;54:S131–55.
[19] Kesharwani P, Jain K, Jain NK. Dendrimers as nanocarriers. Prog Polym Sci. 2014;39(2):268–307.

[20] Moghassemi S, Hadjizadeh A. Nano-niosomes. J Control Release. 2014;185:22–36.
[21] Matsumura Y, Maeda H. EPR effect in tumor targeting. Cancer Res. 1986;46(12):6387–92.
[22] Bertrand N, Wu J, Xu X, Kamaly N, Farokhzad OC. Cancer nanotechnology. Adv Drug Deliv Rev. 2014;66:2–25.
[23] Kamaly N, Xiao Z, Valencia PM, Radovic-Moreno AF, Farokhzad OC. Targeted polymeric therapeutics. Chem Soc Rev. 2012;41(7):2971–3010.
[24] Wang AZ, Langer R, Farokhzad OC. Nanoparticle delivery of cancer drugs. Annu Rev Med. 2012;63:185–98.
[25] Petros RA, DeSimone JM. Strategies in nanoparticle design. Nat Rev Drug Discov. 2010;9(8):615–27.
[26] Yoo JW, Irvine DJ, Discher DE, Mitragotri S. Bio-inspired drug delivery. Nat Rev Drug Discov. 2011;10(7):521–35.
[27] Davis ME, Chen Z, Shin DM. Nanoparticle therapeutics. Nat Rev Drug Discov. 2008;7(9):771–82.
[28] Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer nanomedicine. Nat Rev Cancer. 2017;17(1):20–37.
[29] Wicki A, Witzigmann D, Balasubramanian V, Huwyler J. Nanomedicine in cancer therapy. J Control Release. 2015;200:138–57.
[30] Lanza GM, Wickline SA. Targeted nanomedicine in cardiovascular disease. Nat Rev Cardiol. 2011;8(4):214–23.
[31] Saraiva C, Praça C, Ferreira R, Santos T, Ferreira L, Bernardino L. Nanoparticle-mediated BBB transport. J Control Release. 2016;235:34–47.
[32] Pelgrift RY, Friedman AJ. Nanotechnology in antimicrobial therapy. Adv Drug Deliv Rev. 2013;65(13–14):1803–15.
[33] Kelkar SS, Reineke TM. Theranostics. Bioconjug Chem. 2011;22(10):1879–903.
[34] Mura S, Couvreur P. Nanotheranostics. Adv Drug Deliv Rev. 2012;64(13):1394–416.
[35] Esteva A, Robicquet A, Ramsundar B, et al. Deep learning in healthcare. Nat Med. 2019;25(1):24–9.
[36] Doudna JA, Charpentier E. CRISPR-Cas9 genome editing. Science. 2014;346(6213):1258096.
[37] Stuart MAC, Huck WTS, Genzer J, et al. Stimuli-responsive materials. Nat Mater. 2010;9(2):101–13.
[38] Wilhelm S, Tavares AJ, Dai Q, et al. Analysis of nanoparticle delivery. Nat Rev Mater. 2016;1:16014.
[39] Hare JI, Lammers T, Ashford MB, et al. Challenges in nanomedicine. Adv Drug Deliv Rev. 2017;108:25–38.
[40] Zhang L, Gu FX, Chan JM, Wang AZ, Langer RS, Farokhzad OC. Nanoparticles in medicine: therapeutic applications. Clin Pharmacol Ther. 2008;83(5):761–9.
[41] Alexis F, Pridgen E, Molnar LK, Farokhzad OC. Factors affecting nanoparticle biodistribution. Mol Pharm. 2008;5(4):505–15.
[42] Mitragotri S, Burke PA, Langer R. Overcoming biological barriers. Nat Rev Drug Discov. 2014;13(9):655–72.
[43] Wilhelm S, Tavares AJ, Dai Q, et al. Nanoparticle delivery efficiency. Nat Rev Mater. 2016;1:16014.
[44] Nichols JW, Bae YH. EPR effect: reality and challenges. J Control Release. 2014;190:451–64.
[45] Fang J, Nakamura H, Maeda H. EPR effect enhancement strategies. Adv Drug Deliv Rev. 2011;63(3):136–51.
[46] Sindhwani S, Syed AM, Ngai J, et al. Transport across tumor endothelium. Nat Mater. 2020;19(5):566–75.
[47] Poste G. Bring biomarkers to clinical practice. Nature. 2011;469(7329):156–7.
[48] Henry NL, Hayes DF. Cancer biomarkers. Mol Oncol. 2012;6(2):140–6.
[49] Sawyers CL. The cancer biomarker problem. Nature. 2008;452(7187):548–52.
[50] Parveen S, Misra R, Sahoo SK. Nanoparticles in cancer therapy. Drug Discov Today. 2012;17(7–8):362–8.
[51] Singh R, Lillard JW Jr. Nanoparticle-based drug delivery. Exp Mol Pathol. 2009;86(3):215–23.
[52] Riehemann K, Schneider SW, Luger TA, et al. Nanomedicine overview. Angew Chem Int Ed. 2009;48(5):872–97.
[53] Bendas G. Immunoliposomes in cancer therapy. BioDrugs. 2001;15(4):215–24.
[54] Kirpotin DB, Drummond DC, Shao Y, et al. Antibody-targeted liposomes. Cancer Res. 2006;66(13):6732–40.
[55] Ruoslahti E. Peptides in targeting. Annu Rev Cell Dev Biol. 2012;28:459–82.
[56] Torchilin VP. Multifunctional stimuli-sensitive nanocarriers. Nat Rev Drug Discov. 2014;13(11):813–27.
[57] Karimi M, Ghasemi A, Zangabad PS, et al. Smart nanoparticles. Chem Soc Rev. 2016;45(5):1457–501.
[58] Mura S, Nicolas J, Couvreur P. Stimuli-responsive nanocarriers. Nat Mater. 2013;12(11):991–1003.
[59] Slamon DJ, Clark GM, Wong SG, et al. HER2 in breast cancer. Science. 1987;235(4785):177–82.
[60] Yarden Y, Sliwkowski MX. EGFR signaling. Nat Rev Mol Cell Biol. 2001;2(2):127–37.
[61] Folkman J. Angiogenesis in cancer (VEGF). Nat Med. 1995;1(1):27–31.
[62] Pardridge WM. BBB drug targeting. Nat Rev Drug Discov. 2007;6(7):554–66.
[63] Saraiva C, Praça C, Ferreira R, et al. BBB nanomedicine delivery. J Control Release. 2016;235:34–47.
[64] Libby P. Inflammation in atherosclerosis. Nature. 2002;420(6917):868–74.

[65] Mulder WJM, Jaffer FA, Fayad ZA, Nahrendorf M. Nanomedicine in cardiovascular disease. Nat Rev Cardiol. 2014;11(11):667–79.
[66] Wang L, Hu C, Shao L. Nanotechnology in antibacterial therapy. Int J Nanomedicine. 2017;12:1227–49.
[67] Rai M, Deshmukh SD, Ingle AP, et al. Silver nanoparticles antimicrobial. Biotechnol Adv. 2012;30(3):680–90.
[68] Chen H, Zhang W, Zhu G, et al. Theranostic nanomedicine. Nat Rev Mater. 2017;2:17024.
[69] Jokerst JV, Lobovkina T, Zare RN, Gambhir SS. Nanoparticle imaging. Nanomedicine. 2011;6(4):715–28.
[70] Topol EJ. AI in medicine. Nat Med. 2019;25(1):44–56.
[71] Kourou K, Exarchos TP, Exarchos KP, et al. Machine learning in cancer. Comput Struct Biotechnol J. 2015;13:8–17.
[72] Lino CA, Harper JC, Carney JP, Timlin JA. CRISPR delivery challenges. Drug Deliv. 2018;25(1):1234–57.
[73] Yin H, Kanasty RL, Eltoukhy AA, et al. Non-viral gene delivery. Nat Rev Genet. 2014;15(8):541–55.
[74] Nel AE, Mädler L, Velegol D, et al. Nanotoxicology. Science. 2009;311(5761):622–7.
[75] Fadeel B, Farcal L, Hardy B, et al. Safety assessment of nanomaterials. ACS Nano. 2018;12(11):10582–620.
[76] Etheridge ML, Campbell SA, Erdman AG, et al. Nanomedicine challenges. Nanomedicine. 2013;9(1):1–14.