WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Nano Delivery Systems Shaping the Landscape of Drug Development in Personalized Medicine

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1. Introduction

Nanomedicine, supported globally by public policy and significant investment, is often portrayed as a transformative force in healthcare, promising to revolutionize everything from diagnostics to therapeutic treatments. One of its most significant promises lies in advancing personalized medicine, where diagnostics and treatments are tailored to meet individual needs, creating a more patient-centric approach to healthcare. This article examines the evolving concept of personalized medicine through the lens of nanomedicine research, focusing on insights derived from qualitative interviews with researchers in Canada [1, 2]. It explores how researchers perceive personalized medicine within the context of nanomedicine, identifying two key perspectives: a molecular understanding of individuality and a technical approach to personalization [3]. Nanomedicine, defined as the application of nanotechnology in healthcare, is frequently presented as a revolutionary advancement capable of offering unprecedented technical access to fundamental molecular processes that govern health and disease. However, this portrayal often overlooks the fact that nanomedicine builds upon pre-existing trends rather than representing a complete break from traditional medical paradigms. Specifically, it represents an intensification of the ongoing trend toward the molecularization of medicine, which emphasizes understanding and manipulating biological systems at a molecular level. At the core of this molecularization lies the concept of personalized medicine, which has been the subject of extensive debate and varying interpretations [4, 5].

In nanomedicine, personalized medicine is often envisioned as delivering the right treatment to the right patient based on genetic and other individual-specific characteristics. This perspective aligns with the broader historical trajectory of pharmacogenetics and pharmacogenomics, disciplines that focus on how genetic differences influence drug responses. While these fields initially explored variations in drug metabolism and therapeutic efficacy, advances in genomics have expanded their scope to encompass a more comprehensive understanding of genetic variability in treatment outcomes [6, 7]. Historically, personalized medicine has been analyzed through diverse sociological and cultural lenses. Researchers have examined issues such as the persistence of racial and ethnic categorizations, potential genetic discrimination in insurance systems, and the alignment of personalized medicine with neoliberal ideologies. Scholars have also explored how it reshapes perceptions of risk, disease ontology, and the clinical integration of pharmacogenetic technologies. Additionally, personalized medicine has been situated within broader biomedical trends, highlighting both continuities and changes from earlier medical paradigms [8, 9].

This article aims to clarify how nanomedicine researchers conceptualize personalization and the narratives they construct around it. By analyzing interview data from nanomedicine scientists in Quebec and Ontario, the study identifies distinct patterns in their understanding of personalization. These scientists contribute to shaping the evolving nanomedicine paradigm, though their perspectives are not the sole determining factor [10]. The analysis draws on insights from science studies, emphasizing the non-linear nature of technological innovation, the role of expectations in shaping socio-technical systems, and the importance of context in technological practices. After outlining the technical dimensions of nanomedicine and detailing the study's methodology, the article presents its findings, highlighting the two primary conceptions of personalization. The discussion concludes by synthesizing these perspectives and reflecting on the historical and normative implications of personalization within the context of nanomedicine's development [11].

2. Role of Nanotechnology

Nanotechnology, derived from the Greek word “nano” meaning dwarf, refers to the manipulation and use of materials at a scale ranging from 1 to 100 nanometers (nm). At this size range, materials exhibit unique physical and chemical properties not observed at larger scales or smaller molecular levels. For instance, a DNA molecule is about 2 nm wide, and most virus particles fall within the 5 to 50 nm range. These distinctive properties arise largely from the high surface area of nanoparticles, which results in increased reactivity. Scientists and industries are leveraging these properties to create innovative applications across fields such as medicine, electronics, and materials science [12, 13]. Currently, over 1,000 nanotechnology-enabled consumer products are available, including pharmaceuticals, diagnostic tools, medical devices, and implants [14]. Nanotechnology products of the first generation included simpler nanomaterials such as quantum dots, buckyballs, carbon nanotubes, and tiny particles of titanium dioxide, iron oxide, or

silver. More intricate nanosystems and multipurpose devices are the main focus of the current development of second-generation nanotechnology products [15]. The field of nanomedicine, which includes advanced therapeutics and diagnostics, was created in the healthcare industry as a result of nanotechnology [16]. Numerous medications and medical equipment based on nanotechnology have already received regulatory approval, while numerous others are being studied in clinical trials. By 2012, projections estimated these sales would surpass $12 billion. Drug delivery was the dominant focus, accounting for approximately 75% of all nanomedicine investments, while other applications included new drug formulations, in vivo imaging agents, in vitro diagnostics, biomaterials, and active implants [17, 18].

Nanotechnology is revolutionizing drug delivery systems by enabling precise targeting, improved solubility, controlled release, and longer retention times. Drugs can be incorporated into or attached to nanoparticles, allowing them to cross biological barriers such as the blood-brain barrier [19]. Encapsulation of therapeutic agents within nanoparticles enhances efficacy, reduces systemic toxicity, and improves patient compliance. For example, Elan's NanoCrystal® technology reformulates drugs into nano-sized crystals, increasing their solubility, minimizing side effects, and enabling more convenient tablet forms. In diagnostics, nanotechnology has led to highly sensitive detection methods for diseases and molecular markers. Nanoparticles, such as magnetic iron oxide, have been used to significantly enhance MRI sensitivity for detecting tumor-infiltrated lymph nodes. Similarly, quantum dots—fluorescent semiconductor nanocrystals—are being employed to identify and track cancer cells in the body [20-22].

Beyond drug delivery and diagnostics, nanomedicine encompasses a wide range of applications, including antimicrobial nanocoatings in wound dressings, implants, and catheters. Nanomaterials are also improving biomaterials for implants, bone repair, and dental restorations. In gene therapy, nanotechnology is advancing both viral and non-viral delivery vectors. Although still theoretical, future possibilities include nanoscale robots capable of navigating blood vessels to detect and address early signs of disease. The continued advancement of nanotechnology in medicine promises to revolutionize diagnostics, treatment, and patient care. However, these advancements must be carefully evaluated for safety, toxicity, and long-term effects to ensure their responsible integration into healthcare systems [23, 24].

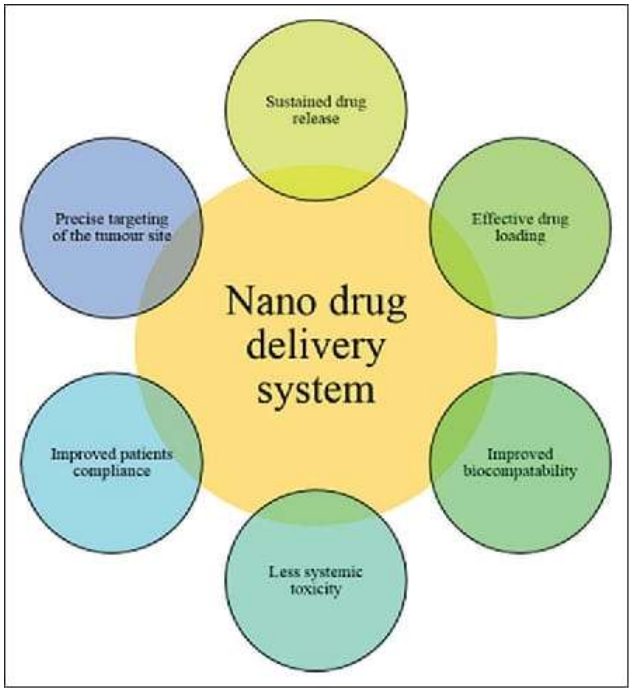

Figure 1: Role of nano-drug delivery system.

3. Application of Personalized medicine

Personalized medicine focuses on delivering the appropriate treatment at the optimal dose to the specific patient. It emphasizes predicting, detecting, diagnosing, and managing diseases through molecular biomarkers, including gene variations, RNA expression, proteins, metabolites, lipids, and other molecular indicators. Nanotechnology plays a significant role in advancing personalized medicine due to its ability to interact at the same molecular scale as these biomarkers, such as DNA, proteins, and cell receptors. This alignment in scale enables nanomaterials to detect biological markers and processes with extraordinary precision, often at the level of single molecules or individual cells, whether in laboratory settings or within living organisms. For instance, researchers have demonstrated the ability to track a single cancer cell tagged with nanomaterials as it moves through an animal's bloodstream, lymphatic system, and tissues using advanced imaging techniques. Overall, nanotechnology holds immense promise for revolutionizing the key areas of personalized medicine [25]. The major categories of applications of nanomaterials to personalized medicine are reviewed below.

3.1. Targeted Therapeutics

Nanotechnology is playing a transformative role in the reformulation of numerous drugs, enhancing properties such as solubility and methods of administration. A particularly significant application within the realm of personalized medicine is the development of innovative strategies to direct drugs specifically to diseased tissues, such as tumors. Presently, only a small fraction of administered cancer therapies and other treatments successfully reach their intended targets, with much of the medication dispersing throughout the bloodstream and potentially causing harmful side effects. Targeted drug delivery not only ensures a more efficient treatment of diseased tissues but also allows for the administration of smaller doses, reducing side effects and improving patient compliance. Nanotechnology facilitates drug targeting through both passive and active mechanisms. Passive targeting leverages the unique size and properties of nanodrugs to enhance their accumulation at specific sites, particularly in tumors [26]. Tumors often exhibit "leaky" blood vessels with large pores, allowing macromolecules up to 400 nanometers in diameter to infiltrate the surrounding tissue. This phenomenon, known as the enhanced permeability and retention (EPR) effect, enables the concentration of nanoscale drugs within tumor regions. Early passive targeting technologies included liposomes—vesicles with a bilayer membrane, hydrophilic on the outside and hydrophobic on the inside—capable of encapsulating drugs. Advances in liposome technology have led to the development of synthetic polymer coatings that shield the agents from immune system attacks.

Although passive targeting is generally seen as a universal mechanism applicable to all patients, recent research suggests its potential for personalized treatment [27]. For example, in a rodent breast cancer study, liposomes containing a contrast agent were used to predict the effectiveness of a nanodrug, liposomal doxorubicin, in reducing tumor growth. Imaging these liposomes revealed tumor vasculature characteristics, enabling the identification of patients likely to benefit most from subsequent nanodrug therapies delivered via similar carriers. The most profound impact of nanotechnology may lie in the creation of highly specific targeted therapeutics. This involves linking nanodrugs or drug carriers with affinity ligands such as antibodies, peptides, or small molecules that bind precisely to target cells, such as tumor cells. Once bound, the drug is delivered into the target cell through receptor-mediated endocytosis. Researchers are actively exploring a wide range of ligands, nanocarriers, and methodologies to develop these targeted nanotechnology-based treatments [28, 29].

3.2. Molecular Imaging Agents

Nanotechnology offers enhanced sensitivity and specificity for molecular diagnostics, which are essential for advancing personalized medicine. Molecular imaging involves various techniques to analyze molecular signatures, and a range of nanomaterials, such as nanotubes, dendrimers, liposomes, and quantum dots, have been developed as diagnostic probes. While many of these probes were initially designed for use in vitro, they are increasingly being adapted for in vivo applications [30, 31]. Because nanotechnology may target specific tissues or cells instead of evaluating the heterogeneous mix of cells usually found in tumor or sick tissue samples, it offers a substantial benefit in diagnostics. To make extremely sensitive and precise imaging probes for tumor markers, for example, quantum dots (QDs) can be conjugated with antibodies [32]. These QDs consist of semiconductor cores, often consisting of inorganic crystals such as cadmium selenide, that have a diameter of 2 to 10 nanometers and are covered with an organic coating and a zinc sulfide shell. In order to engage with cell surface receptors or other biomolecules, this coating can bind to a variety of ligands. Compared to traditional organic dyes, QDs exhibit greater resistance to photobleaching, brighter fluorescence, and tunable emission wavelengths based on their size, allowing flexibility in imaging live tissues and monitoring multiple biological functions or structures simultaneously. Although initially used in vitro, QDs are now being developed for in vivo applications, with studies demonstrating their ability to detect and quantify tumor antigens in tissue samples [33-36].

Beyond specificity, nanoparticles enhance the sensitivity of diagnostic probes. Traditional imaging techniques often struggle to detect molecular markers due to the low concentration of imaging agents [37]. However, nanotechnology probes, with their larger surface area, can carry a higher payload of imaging agents, resulting in stronger signals. Unlike conventional methods like immunohistochemistry (IHC) and fluorescence in situ hybridization (FISH), which can yield subjective and inconsistent results at low antigen levels, multiplexed QD probes offer objective, quantitative measurements of tumor markers even at low concentrations. This capability is particularly valuable for cancers such as breast cancer, where accurately profiling tumors with low levels of HER2 receptors is critical for determining the effectiveness of trastuzumab (Herceptin) treatment [38, 39].

3.3. In Vitro Diagnostics

Developments in nanotechnology have completely changed the process of creating in vitro diagnostic tools that can identify proteins and other disease markers in samples taken in the field or in a clinical environment. Techniques like microarray DNA chips and microfluidic systems, which were first developed in the 1980s, now use nanotechnology to greatly increase resolution and data storage. Nanochips, for instance, have enabled the creation of protein arrays, facilitating highly sensitive diagnostics that can identify even a single molecule of the target biomarker. These devices are also designed for point-of-care applications, offering swift and precise results [40]. Lab-on-chip technologies are a prominent application of nanotechnology, integrating multiple functions like sample mixing, transport, detection, and data processing within a single miniature chip. Carbon nanotubes, known for their exceptional physical, electrical, and chemical properties, play a pivotal role in these applications. Lab-on-chip systems are especially promising for resource-limited settings due to their affordability, reliability, and durability. In developed countries, they provide the advantage of performing routine tests and delivering results directly in a physician's office, bypassing the need for external laboratories. Numerous products and applications in this domain are currently under development and have been extensively reviewed [41].

Nanotechnology is also at the forefront of advancing DNA sequencing technologies. While existing high-throughput sequencing methods are often slow and costly, innovations like DNA nanopore technology are poised to make large-scale DNA sequencing feasible and affordable. For instance, microfluidic

polymerase chain reaction (PCR) devices and nanopore systems allow for rapid, cost-effective replication and analysis of small genetic material samples, addressing critical limitations in speed and expense. While early nanodrugs were primarily monofunctional, modern nanotechnology enables the creation of multifunctional products that combine diagnostic and therapeutic capabilities within a single entity. Nanostructures provide a large surface area for attaching multiple functional components, paving the way for innovations in targeted and personalized medicine [42]. One prominent example is dendrimers—core-shell nanostructures with multiple "arms" capable of carrying various functional moieties. For instance, one arm can attach to a targeting molecule that binds to receptors on specific cells, such as tumor cells, while others may carry sensors for external detection or therapeutic agents that release upon activation. Additional functionalities under development include components that can "report back" on therapeutic efficacy, such as signaling tumor cell destruction through non-invasive imaging. These multifunctional nanostructures exemplify the potential of nanotechnology to integrate targeting, imaging, therapy, and monitoring into a unified platform [43].

3.4. Role of nanobiotechnology in personalized oncology

Nanobiotechnology is instrumental in advancing personalized approaches to cancer management by improving the detection of cancer biomarkers and integrating diagnostics with therapeutics. Below are examples of its applications:

3.4.1. Targeted Paramagnetic Nanoparticles for Molecular MRI

Paramagnetic nanoparticles have been designed to noninvasively detect early angiogenesis associated with nascent melanoma tumors. These nanoparticles are loaded with thousands of contrast-enhancing metal molecules used in conventional MRI scans. Their surfaces are functionalized with ligands that bind specifically to newly forming blood vessels, a hallmark of tumor sites. This targeted approach allows for the detection of sparse biomarkers using molecular MRI, even before the growths become visible on conventional MRI scans. Early detection is particularly beneficial for melanoma, as it increases the likelihood of successful treatment. The same nanoparticles that are employed for imaging can also minimize systemic toxicity by delivering high doses of anticancer medications straight to the tumor location. Comparing MRI scans before and after therapy allows doctors to assess the effectiveness of treatment. This strategy tackles important facets of tailored cancer care, such as theranostics (a combination of diagnostics and treatments), early detection, and therapy efficacy monitoring [44, 45].

3.4.2. Dendrimers for drug delivery in oncology

Dendrimers are highly versatile 3D nanoscale structures with a core-shell architecture. Their physical and chemical properties can be precisely engineered for various applications, particularly in oncology. Dendrimers are primarily utilized in drug delivery systems, but they also have potential in the development of new pharmaceuticals with novel mechanisms of action. Polyvalent dendrimers can interact with multiple drug targets simultaneously, enhancing therapeutic precision. For example, dendrimers can be conjugated with biofunctional molecules like folic acid or complementary DNA oligonucleotides to create clustered constructs [46]. These targeted structures specifically bind to cancer cells that overexpress high-affinity folate receptors, enabling precise delivery of therapeutics to tumor sites. This targeted approach minimizes off-target effects and maximizes the therapeutic impact, making dendrimers a promising tool in the field of nanomedicine. These advancements exemplify how nanobiotechnology contributes to personalized cancer management by combining early detection, targeted therapy, and treatment monitoring into a unified framework [47].

Table 1: Nanomedicine and its application in personalized medicines [47].

Nanomedicine Approach	**Application in Personalized Medicine**	**Examples**
Nanoparticles for Drug Delivery	Targeted drug delivery based on patient-specific biomarkers	Lipid nanoparticles for mRNA vaccines, polymeric nanoparticles for cancer therapy
Nanodiagnostics	Early and precise disease detection tailored to genetic profiles	Quantum dots for biomarker detection, nanosensors for real-time glucose monitoring
Nanocarriers for Gene Therapy	Personalized gene editing and therapy for genetic disorders	CRISPR-Cas9 delivery via lipid nanoparticles for genetic diseases
Nanobiosensors	Real-time monitoring of patient-specific biomarkers	Wearable biosensors for continuous glucose and lactate monitoring
Nanoformulations of Therapeutics	Optimized drug bioavailability and reduced side effects	Nano-liposomal formulations of chemotherapeutics like Doxil (doxorubicin)
Nanovaccines	Custom vaccine design based on individual immune profiles	Personalized cancer vaccines using nanoparticle adjuvants
Nanorobotics	Precision therapy and disease intervention at the cellular level	DNA-based nanorobots for targeted drug release in tumors

4. Nano delivery system for shaping personalized medicine

4.1. Discovery and Delivery of Personalized Nanomedicines

Nanotechnologies, including nanoparticles and nanodevices like biosensors and biochips, are revolutionizing drug discovery and development by enhancing the precision of these processes. Some current medications are being personalized, while others are designed with personalization in mind from the outset. Nanobiotechnology plays a pivotal role in advancing these personalized pharmaceutical solutions [48, 49].

Drug delivery remains a critical component of modern medicine, emphasizing targeted delivery to specific organs or sites of action while overcoming biological barriers to ensure safety and efficacy. By conjugating nanocarriers with specific ligands or aptamers, drug delivery systems achieve precise targeting, resulting in improved therapeutic outcomes. Nanoparticle-based advancements in drug delivery are driving progress in personalized medicine. Furthermore, nanotechnology has significantly enhanced the delivery of biologic therapies, such as cell and gene therapies, which are highly suited to personalized treatments [50, 51].

4.2. Role of Nanobiotechnology in Personalized Cancer Treatment

Nanobiotechnology is a cornerstone in developing tailored cancer therapies. It enhances the detection of cancer biomarkers, which serve as the foundation for creating both diagnostic tools and treatments. For instance, targeted paramagnetic nanoparticles are employed to noninvasively detect early angiogenesis associated with melanoma [52]. These nanoparticles, loaded with contrast-enhancing metals, bind to newly formed blood vessels at tumor sites, enabling molecular MRI detection of sparse biomarkers before conventional MRI can identify the growths. This early detection approach can improve treatment efficacy, especially for melanoma. Additionally, these nanoparticles can deliver high doses of anticancer drugs directly to tumors, minimizing systemic toxicity. The ability to detect, treat, and monitor efficacy exemplifies key aspects of personalized cancer therapy [53].

Dendrimers, a unique class of three-dimensional nanoscale structures, offer precise control over their physical and chemical properties, making them invaluable for oncology. These structures are particularly effective in drug delivery and the development of novel therapeutics. By conjugating dendrimers with biofunctional molecules like folic acid or complementary DNA oligonucleotides, they can target cancer cells overexpressing specific receptors, such as the high-affinity folate receptor. Polyvalent dendrimers, capable of interacting with multiple drug targets simultaneously, hold promise for creating innovative targeted cancer treatments [54, 55].

Multifunctional nanoparticles are increasingly being explored for personalized oncology. When conjugated with targeting ligands such as monoclonal antibodies, peptides, or small molecules, these nanoparticles can deliver therapeutic agents to tumors with remarkable specificity and affinity. These advancements pave the way for personalized cancer care, where detection, diagnosis, and treatment are tailored to an individual's molecular profile [56].

4.3. Nanobiotechnology in Personalized Neurological Treatments

Advances in nanobiotechnology are transforming the understanding and management of neurological disorders. Improved molecular diagnostics facilitated by these technologies enable the integration of diagnostic and therapeutic approaches, a key step toward personalized neurology. Nanotechnologies also support the development of targeted therapies based on the underlying mechanisms of neurological diseases. For instance, nanoparticle-mediated drug delivery to the brain is a vital component of personalized treatment strategies for central nervous system disorders [57-59].

4.4. Nanotechnology in Personalized Cardiovascular Medicine

Cardiovascular diagnosis and treatment are being reshaped by nanosystems that combine diagnostic and therapeutic functions. Perfluorocarbon nanoparticles, for example, are utilized for both targeted drug delivery and molecular imaging in cardiovascular diseases [60, 61]. This dual functionality allows visualization of disease states while ensuring precise drug delivery to affected areas. Image-based therapies employing site-specific agents provide assurance that treatments are reaching their intended targets and having the desired molecular effects, key elements of personalized therapy [62].

Molecular imaging techniques in coronary artery disease focus on biomarkers linked to atherosclerosis development. Engineered nanoparticles act as transport systems for diagnostic and therapeutic agents, contributing to the management of coronary artery disease with a high degree of precision and personalization [63].

4.5. Role of nanomedicine in personalized medicine for targeted drug delivery

Under the direction of Professor Lozano of the University of Castilla-La Mancha in Albacete, researchers created oral hybrid systems that use nanoemulsions to treat ulcerative colitis in the area of hybrid nanoparticles for colon administration. Encapsulated in a pectin hydrogel matrix, these systems were intended to break down in the gastrointestinal tract and allow the colon's nanoemulsions to release in response to stimuli. In the production of hybrid systems, the condensation process affects both the enzyme-triggered release mechanism and the enzymatic breakdown of pectin, according to the study [64]. At the University of the Basque Country, Prof. Pozo-Rodríguez and associates from the Centro de Investigación Lascaray Ikergunea investigated lipid-based vectors for the delivery of nucleic acids and their potential applications in Fabry disease (FD). Their systematic review and meta-analysis highlighted the utility of lipid-based systems as versatile, non-viral carriers for nucleic acids, such as pDNA and mRNA, allowing surface

modification to control biodistribution after intravenous administration. The study emphasized the need for organ-specific targeting strategies, noting a scarcity of research on kidney-targeted delivery and limited focus on the heart. The authors stressed the importance of designing high-quality, scalable, and clinically translatable active-targeted carriers [65].

In the domain of cerebral delivery and anti-inflammatory interventions, a particular study has successfully developed a sophisticated in vitro model of the BBB. This model was applied to assess the effects of sonopermeation on the transport of two agents: the polymeric drug carrier pHPMA and the antiviral compound ribavirin. Experimental methodologies were executed under both normative and inflammatory scenarios, utilizing targeted and untargeted iRGD-microbubbles (MB) to effectuate temporary and spatial modulation of BBB permeability. The co-culture model, which incorporates human cerebral capillary endothelial cells alongside human placental pericytes, demonstrated suitable transendothelial electrical resistance. Inflammatory responses triggered by tumor necrosis factor (TNF) resulted in RGD-coated microbubbles (MB) efficiently adhering to and permeabilizing the inflamed co-culture model, consequently significantly improving the delivery of Atto488-pHPMA and ribavirin. This methodology offers a significant framework for investigating BBB inflammation and the underlying mechanisms governing the transport of nanoparticle-based bioactive molecules [66]. Additionally, Professor Lammers and his research team examined tunable polymeric micelles formulated for the concurrent administration of taxanes and corticosteroids, intended to reduce inflammation and infusion-associated negative reactions, thereby optimizing the tumor microenvironment to improve nano-chemotherapy results. The double-loaded micelles revealed significant encapsulation efficacy, characterized by a defined release profile—PTX displaying a progressive release whereas DEX was released instantaneously. The study demonstrated that the retention of hydrophobic drugs within micelles is significantly influenced by the drugs' hydrophobicity and molecular weight, highlighting the micelles' versatility for co-delivery applications [67].

4.6. Pharmacogenomics in personalized medicine

Pharmacogenomics, though linked by name to genomics, has its origins in the 1950s with the emergence of pharmacogenetics. This field initially focused on understanding how individual differences influence drug metabolism, excretion rates, and therapeutic effectiveness. With advancements in genomic research, particularly following the Human Genome Project, the principles of pharmacogenetics were expanded to a genomic level under the umbrella of pharmacogenomics, connecting drug interactions to variations in the human genome. While the terms pharmacogenomics and pharmacogenetics are sometimes used interchangeably, they are occasionally distinguished and debated [68, 69]. By the early 2000s, both terms had become closely associated with personalized medicine. Much of the work in the social sciences on personalized medicine has focused on its relationship with pharmacogenomics and pharmacogenetics. This includes examining how racial and ethnic categories are reimagined in the post-genomic era, addressing concerns about genetic discrimination in areas such as insurance, and exploring its alignment with neoliberal perspectives. Other areas of study have included the emergence of new health-related risks, evolving conceptions of disease, and the clinical integration of pharmacogenetics. Additionally, personalized medicine has been contextualized within broader trends in biomedicalization, with analyses highlighting both the continuities and changes in personalization from earlier practices dating back to the 19th century [70, 71].

5. Nano Delivery Systems for shaping Personalized Medicine

The evolution of personalized medicine aims to tailor treatments to an individual's genetic profile, disease characteristics, and biological responses. One of the most promising advancements in this field is the integration of nanotechnology-based drug delivery systems. These nano delivery systems improve the precision, efficacy, and safety of therapeutics by enabling targeted and controlled drug release. By leveraging nanoparticles, liposomes, dendrimers, and other nanoscale carriers, modern medicine can optimize treatments for diverse patient populations while minimizing adverse effects. Nanotechnology has transformed drug delivery by addressing key challenges associated with conventional therapies, such as poor solubility, off-target effects, and low bioavailability. Personalized medicine seeks to optimize therapeutic efficacy by customizing drug formulations based on an individual's genetic makeup, metabolism, and disease progression. Nano delivery systems enhance this approach by ensuring precise drug localization, sustained release, and reduced systemic toxicity. Types of Nano Delivery Systems in Personalized Medicine [72].

5.1. Liposomes

Liposomes are spherical vesicles composed of lipid bilayers, which enhance drug solubility and protect bioactive molecules from degradation. They can be functionalized with targeting ligands to ensure site-specific drug delivery. In oncology, liposomal formulations such as Doxil (liposomal doxorubicin) improve drug accumulation in tumors while minimizing cardiotoxicity [73].

5.2. Polymeric Nanoparticles

Polymeric nanoparticles, typically composed of biodegradable polymers like poly(lactic-co-glycolic acid) (PLGA) or chitosan, offer controlled drug release and enhanced cellular uptake. Their tunable properties allow for the incorporation of multiple therapeutic agents, making them ideal for personalized treatments (Danhier et al., 2012). These nanoparticles are particularly useful in gene therapy and vaccine delivery, where sustained antigen release enhances immune response [74].

5.3. Dendrimers

Dendrimers are branched polymeric structures with a high degree of surface functionalization. Their well-defined architecture enables precise drug conjugation and targeted delivery. Dendrimer-based drug carriers, such as poly(amidoamine) (PAMAM) dendrimers, have shown promise in cancer therapy, gene delivery, and antimicrobial applications [75].

5. 4. Inorganic Nanoparticles

Inorganic nanoparticles, including gold nanoparticles, quantum dots, and mesoporous silica nanoparticles, have gained attention for their diagnostic and therapeutic capabilities. Gold nanoparticles, for example, facilitate targeted photothermal therapy, enabling the selective destruction of cancer cells while sparing healthy tissues. Additionally, quantum dots serve as fluorescent markers for high-resolution imaging in personalized diagnostics [76].

The future of nano delivery in personalized medicine lies in the integration of artificial intelligence (AI) and machine learning (ML) for predictive modeling and treatment optimization. AI-driven platforms can analyze patient-specific data to design customized nanoformulations, improving therapeutic outcomes (Yu et al., 2020). Additionally, the development of biodegradable and biocompatible nanomaterials will further enhance the safety profile of these delivery systems [77, 78].

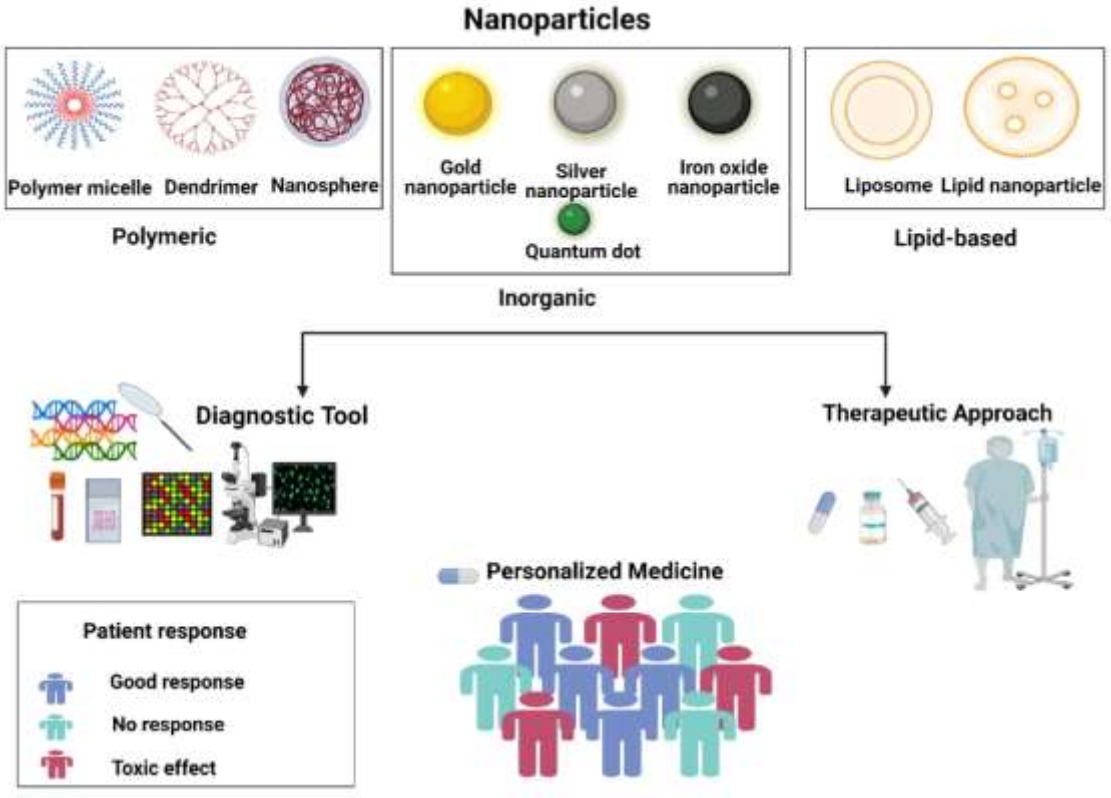

Figure 2: Different nanotechnology used for personalized medications.

6. Future Prospects

Nanomedicine and personalized medicine are already being utilized in clinical settings, though they have not yet been formally recognized as distinct medical specialties. These fields will continue to evolve and influence the future of healthcare. While safety and regulatory concerns surrounding nanomedicine are actively being studied, ethical and economic challenges associated with personalized medicine are also being addressed. Not all diseases require nanomedicine or personalized treatment, and ongoing research is identifying conditions where these approaches are both safe and cost-effective. The primary objective of personalized medicine is to enhance healthcare through innovative technologies, with nanobiotechnology playing a crucial role in integrating diagnostics and therapeutics—an essential aspect of personalized treatment. Advancements in nanobiotechnology, particularly in neurology, are expected to improve our understanding of neurological disorders, facilitate drug discovery, and enhance drug delivery to the central nervous system. By refining molecular diagnostics for neurological conditions, nanobiotechnology will enable better integration of diagnostics with treatment, supporting the development of personalized neurological care [78, 79].

Nanosystems capable of simultaneously diagnosing diseases and administering targeted therapies are revolutionizing medical treatment. For example, perfluorocarbon nanoparticles serve a dual purpose in cardiovascular medicine by enabling both targeted drug delivery and molecular imaging, allowing for the visualization of disease progression and precise treatment at affected sites. Image-guided therapeutics using site-specific agents can help confirm

that drugs are reaching their intended targets and producing the desired molecular effects, which is critical for personalized therapy. In coronary artery disease, molecular imaging techniques focus on detecting biomarkers linked to atherosclerotic lesion formation. Additionally, bioengineered nanoparticles can act as carriers for diagnostic or therapeutic agents, contributing to more effective management of cardiovascular conditions [80, 81].

The discipline of nanomedicine has facilitated the emergence of a variety of innovative nanomaterial platforms. With the advancement of nanomedicine-enhanced monotherapies into clinical trials, following promising results from preliminary human research, the next pivotal stage will involve the clinical deployment of combination nanotherapies. However, an enduring barrier within the expansive pharmaceutical sector remains the inefficacy of dose-escalation or additive-design approaches in the establishment of combination therapies. Mitigating this challenge will be essential for the growth of the nanomedicine sector, especially as nanotechnology-oriented drug delivery frameworks and imaging solutions become more complex. Contemporary nanomedicines are now being meticulously designed to deliver multiple forms of therapeutic payloads, or alternatively, various classes of nanomaterials are being co-administered as combination therapeutic modalities. This review accentuates the use of the ND (nanodiamond) platform to showcase particular applications—such as magnetic resonance imaging (MRI) and oncological therapies—where NDs display a considerable superiority over standard treatment techniques. A recent development at the junction of engineering systems identification and nanodiamond-based pharmaceutical delivery has indicated that combinations of nanodiamond and drugs can be optimized across multiple parameters independently of the fundamental mechanisms involved. This progress concurrently addresses the challenges associated with enhancing drug discovery while utilizing nanomedicine to further improve both therapeutic efficacy and safety [81-83].

7. Conclusion

Both nanomedicine and personalized medicine have asserted their relevance within the clinical milieu, although they have not yet received formal acknowledgment as discrete medical specialties. Both disciplines are foreseen to partake in persistent interaction and growth, thereby considerably affecting the future landscape of medical practice. The safety and regulatory dimensions of nanomedicine are currently under scrutiny, alongside the ethical and economic considerations pertaining to personalized medicine, which are concurrently being addressed. It is imperative to recognize that not every ailment demands the utilization of nanomedicine or personalized medicine; therefore, distinct sectors where these strategies reveal safety, effectiveness, and cost-efficiency are progressively being identified. The overarching goal of personalized medicine is to enhance healthcare delivery through the implementation of innovative technologies. Within this context, nanobiotechnology is poised to play a pivotal role in the amalgamation of diagnostic and therapeutic modalities, which is a crucial element of personalized medicine. The burgeoning area of research in personalized or precision medicine is witnessing an increase in prominence, highlighting a bespoke diagnosis founded upon an individual's genetic makeup, along with specific interventions aimed at particular health disorders. This framework evaluates the genetic, phenotypic, and environmental influences of a patient or a cluster of similar patients, all of which may alter the safety and effectiveness of particular therapeutic approaches. In recent years, investigators have actively pursued the integration of various aspects of nanotechnology for application within personalized medicine.

Nanomedicine has significantly broadened the horizons not only for drug delivery mechanisms but also for molecular and genetic diagnostic endeavors. Personalized medicine can leverage nanomedicine to enhance binding affinity, improve bioavailability and biocompatibility, and achieve optimal therapeutic efficacy through a controlled drug release mechanism, thereby ensuring that the therapeutic agent reaches the appropriate target, in the correct patient, at the precise moment. Additionally, it can facilitate a deeper understanding of an individual's genomic makeup, thus enabling the formulation of endpoint strategies for both diagnosis and therapeutic interventions. Laboratory-synthesized nanoparticles have demonstrated encouraging outcomes, suggesting that it may only be a matter of time before nanomedicine is employed on a substantially larger scale within the realm of personalized medicine. Both nanomedicine and personalized medicine encompass a broad spectrum of possibilities and have the potential to collectively represent the future of medical practice. These systematically developed therapies have significantly surpassed the efficacy and safety metrics associated with randomly selected drug combinations. Furthermore, the utilization of experimental data to construct phenotypic response maps has inherently validated the selected lead combinations. The integration of nanomaterials with targeted drug compounds through engineering optimization platforms has the potential to truly refine drug dosage combinations tailored to specific indications. This advancement is poised to yield unparalleled improvements in patient treatment outcomes against some of the most formidable diseases of our era.

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