Chapter 4
Nanomedicine:
A New Frontier in Drug Delivery Systems

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ABSTRACT

The chapter explores the transformative potential of nanomedicine in revolutionizing drug delivery. Nanomedicine, combining nanotechnology and medicine, offers innovative solutions for healthcare. It delves into advancements enabling targeted and controlled release of therapeutics, improving treatment efficacy while reducing side effects. Beginning with an introduction to nanomedicine's applications, it discusses recent breakthroughs such as nanoparticle-based delivery systems and targeted therapy nanocarriers. Real-world case studies illustrate nanomedicine's efficacy across various diseases. Addressing challenges in translation to clinical practice, including safety and regulatory hurdles, it emphasizes collaborative efforts among stakeholders. Looking forward, ongoing research for safer and more efficient drug delivery systems is highlighted, stressing the need for continued innovation. The chapter aligns with the book's theme of showcasing cutting-edge biomedical developments to improve healthcare.

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Figure 1. Role of nanomedicine in drug delivery system are listed below (Man & Lammers, 2018; Ochekpe et al., 2009; Suri et al., 2007; van der Meel et al., 2019)

Aspect	Description
Targeted Drug Delivery:	To achieve targeted delivery, targeting moieties can be conjugated with nanostructures, allowing for the manipulation of the linkage between the polymer and the active ingredient. This allows for control over the release site and duration of the drug. Drugs enclosed in nanostructures can be shielded from the gastrointestinal tract's hydrolytic and enzymatic breakdown by these structures.
Improved Bioavailability:	Because they have specific uptake mechanisms like absorptive endocytosis, they increase the oral bioavailability of drugs.
Improved Drug Solubility:	supply drugs that are extremely water insoluble and can avoid the liver, preventing the integrated drug's first pass metabolism.
Extended Circulation Time:	capable of staying in the bloodstream for extended periods of time.
Overcoming Biological Barriers:	Using nanostructures, such as polymeric nanoparticles, is a non-invasive way to cross the blood-brain barrier and treat inflammatory, cerebrovascular, and neurodegenerative illnesses.
Personalized Medicine:	Nanomedicine and other advanced drug delivery technologies allow for the customization of treatments based on individual patient characteristics, such as genetic makeup or disease stage. Tailored drug delivery systems contribute to the concept of personalized medicine.
Combination Therapy:	Combination therapies may be possible owing to the potential of nanoparticles to enable the simultaneous delivery of several therapeutic agents. Cancers are treated with a combination of surgery, radiotherapy, chemotherapy, and/or immunotherapy, depending on their location, grade, and stage(4)
Reduced Side Effects:	allowing the integrated medication to be released gradually and continuously, reducing plasma fluctuations and the likelihood of unwanted drug reactions.
Enhanced Cellular Uptake:	Because of their small size, nanostructures can easily enter tissues and be taken up by cells, facilitating the effective delivery of medications to their sites of action. It was discovered that the absorption of nanostructures was 15–250 times higher than that of microparticles in the 110μm range.
Multifunctional Nanocarriers:	When utilized as drug delivery vehicles, nanoparticles are typically less than 100 nm in one dimension and comprise various biodegradable substances like metals, lipids, or natural or synthetic polymers.
Imaging and Diagnosis	Drug distribution and therapeutic response can be tracked in real time by combining imaging agents with drug-loaded nanoparticles.
Research and Development	Developing drug delivery systems through nanotechnology can lead to the expansion of drug markets. With the use of nanotechnology, current medications can be reformulated to increase their shelf life, perform better, become more palatable due to their increased efficacy, improve patient adherence and safety, and ultimately lower medical expenses.

NANOMEDICINE AND DRUG DELIVERY

Overview of Nanotechnology-Enabled Drug Delivery

Nanotechnology-enabled drug delivery involves the implementation and modification of materials and structures at the nanoscale (ranging from 1 to 100 nanometers) with the aim of improving the administration, targeting, and effficacy of medicinal substances (Annisa & Hendradi, 2023). The emerging areas of nanomedicine and nano-delivery systems are comparatively new, yet these are expanding rapidly(Joginder & Anand, 2022). These nanoparticlesconsist of polymers, proteins, lipids, metallic materials, etc., and have distinctive properties such as enhanced surface area and the capacity to overcome biological bar-

have been developed for tumor-specific drug delivery. pH-sensitive carriers are also developed in order to increase the contrast between intracellular and extracellular drug release. In thermosensitive drug carriers, drug release is caused by temperature-induced phase transition of the polymer (Lee & Yeo, 2015).

Drug Release Control in Nanocarriers to Enhance Drug Targeting

More than one mechanism contributes to drug release from nanocarriers in general, albeit one may be more influential than the other. For example, drug release in drug-loaded nanogels coated with a polymer membrane is controlled by swelling as well as diffusion through the membrane.

Many nanoparticles are thought to have improved pharmacokinetic properties because of their physical nature and decreased size; they can target specific cells for selective action dependent on the particle type. These particles can easily penetrate target cells and accumulate into subcellular structures, where they can modify cellular processes. Nanoparticles that are widely used in research for therapeutic purposes include encapsulated mRNA (siRNA) or DNA (in gene therapy), inorganic metal and metal complexes, or chemotherapeutic agents with pharmacologic abilities. Different nanoparticle delivery systems have been developed, some of which include liposomes, micelles, chitosan, and synthetic dendrimers. The entrapment of both hydrophobic and hydrophilic drugs into liposomes is possible, and this helps to bypass the toxicity associated with anticancer drugs. liposomal encapsulation represents an effective route that enhances the drug therapeutic effect. In addition, modification of liposomes allows for passive or active tumor targeting (Yusuf et al., 2023). This mechanism allows for an effective drug payload into malignant tumor cells while having little impact on non-malignant cells. Encapsulation of doxorubicin within the DPPC-based liposome enhances the cytotoxicity of the drug and at the same time suppresses the toxic side effects, thus improving the antitumoral therapeutic efficacy in comparison to conventional doxorubicin.

Mechanism of Nanomedicine and Nanomedicine Drug Delivery System vs. Traditional Drug Delivery System

To state the fact that, nanomedicines show a numerous mechanism regarding the severity and type of disease it is used for. Such as the liposomal formulation mechanism which is a crucial for the treatment of cancer patient, cannot be used for the treatment of cardiovascular patient. But all the nanomedicines have a common mechanism in which they make the drugs well-suspended in an aqueous solution so that they can avoid premature inactivation or clearance in the body circulation during treatment; they can also increase the permeability and retention effect, reduce the non-specific damage to the body and decrease the side effects.

Contrast between nanomedicine drug delivery systems (NDDS) with traditional drug delivery systems (TDDS) can be stated as follows:

- NDDS provide enhanced bioavailability, reduced drug degradation, and improved patient compliance compared to TDDS.
- NDDS is better than TDDS in lowering required does and increasing site specification.
- The diseased cells show a higher uptake of nanomedicine, without affecting the surrounding healthy tissues, hence minimizing side effects which confirm more effective disease management.
- Apart from that, NDDS exhibit a superior control over drug release, targeting capabilities, and are a promising alternative to TDDS, especially in the treatment of cancer and chronic diseases.

Here, Magnetic NPs (MNPs) provide the targeted delivery of drugs which is a kind of nano-scale material composed of magnetic metal such as iron, cobalt, and nickel that respond to an applied magnetic field. MNPs have been designed and synthesized as a core shell structure coated with silica, gold, or polymers making it easier to functionalize the NPs and load drugs. when subjected to external magnetic field, silica-coated magnetic nanocapsules (SiMNCs) can traverse normal BBB and achieve on-demand drug release in brain. The magnetic nanostructures are fabricated using thermosensitive polymers which increase drug release by the magnetocaloric effect. Additionally, drug carriers based on MNPs control release of drugs through an applied magnetic field, which is highly effective for low diffusivity macromolecules.

Another major treatment for CNS in today's era is the pH Responsive Drug Delivery in which the novel NPs known as polymeric expansible NPs (eNPs) are being used. This kind of materials swell and expand 2–10× in diameter when it is exposed in a moderately acidic environment. Some of the diseases have a different pH in the lesion such as stroke, thus, the feature of eNPs make it realized for specific drug delivery. When reaching to the target site, the drug-loaded eNPs swell due to the acidic environment. As a result, the drugs are released through the gaps of expanded eNPs (Feng et al., 2020). Thus, the drugs are delivered precisely without any external stimuli.

Cardiovascular disease (CVD): Cardiovascular disease (CVD) encompasses a group of disorders that involves the heart and vasculature. CVD has been one of the leading causes of mortality for decades, accounting for virtually 1/3 of all deaths in the world. Endothelial-selective delivery of therapeutic agents would provide a benefecial tool for modifying vascular function in various cardiovascular diseases.

Currently, a novel nanoparticulate drug delivery technology has been developed that mimics platelet binding to the damaged vessel wall under physiological flow conditions. Glycoprotein Ib (GPIb) has been chosen as the targeting ligand and conjugated to nanoparticles due to its role in platelet adhesion to the vascular wall under high shear flow conditions is well-recognized. Dexamethasone-loaded biodegradable poly (d,l-lactic-coglycolic acid) (PLGA) nanoparticles heve been formulated using a standard emulsion method in which conjugation of GPIb to PLGA nanoparticles increased particle adhesion onto targeted surfaces and increased cellular uptake of these nanoparticles by activated endothelial cells under shear stresses. Furthermore, these nanoparticles also provide a controlled release of the model drug. Therefore, these drug-loaded, GPIb-conjugated PLGA nanoparticles are being used as a targeted and controlled drug delivery system to the site of vascular injury for treatment of cardiovascular diseases (Gundogdu et al., n.d.).

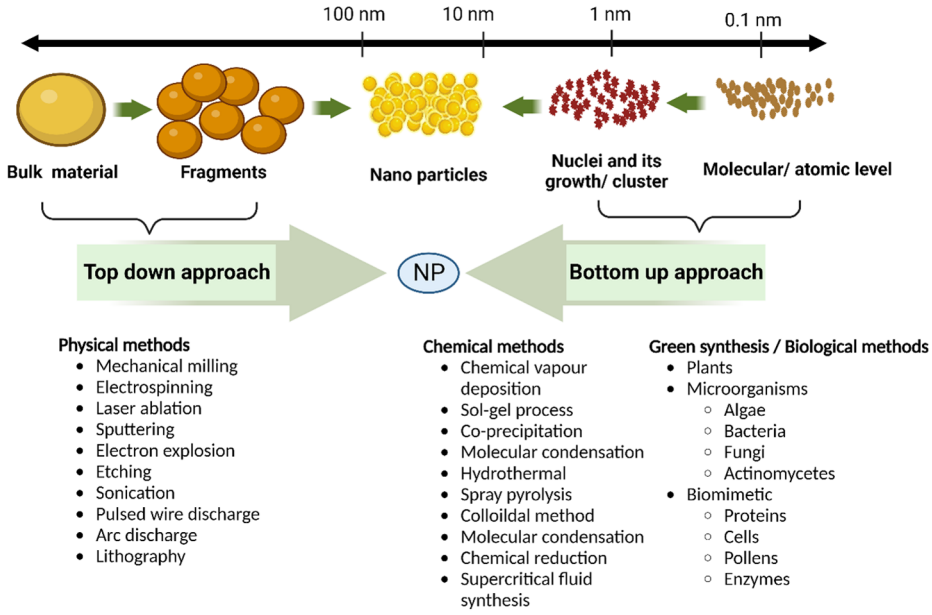
Despite liposomes being crucial for nanomedicines, recently, in the drug market, there is no liposomal formulation approved for the treatment of cardiovascular disease. However, several innovative examples of liposomal technologies have been developed for the treatment of cardiovascular disease.

RECENT ADVANCEMENTS

Nano-Particle Based Drug Delivery System

The chemical and physical characteristics of NPs (Nano particles) make the efficient DDSs (Drug Delivery Systems) that have the potential to improve the bioavailability, drug carrying capacity, stability for the drugs within the body, controlled release, and targeted delivery (Sajid & Płotka-Wasylka, 2020). The NPs also have the ability to remain in the blood for long period. As the particle surface is coated

Figure 2. Some approaches of NPs synthesis



nanosuspensions, nanoparticles/nanospheres, nanoemulsions are nanotechnology based formulation which can significantly increase bioavailability of drug (Kagkelaris et al., 2022).

NANOPARTICLE FORMULATION AND DESIGN

Nanoparticle Synthesis Methods

Nanoparticles can be synthesized in various sizes, shapes, and compositions, using materials such as polymers, metals, and carbon compounds (Mistretta et al., 2023). The synthesis of nanomaterials can be accomplished through two prominent approaches – one is the Top–down approach, another is bottom-up approach (Baig et al., 2021; Goutam et al., 2020; Paramasivam et al., 2021). If we come to methods, there are three types of methods for synthesizing nanoparticles- physical method, chemical method, and biological method aka green synthesis (Altammar, 2023; Goutam et al., 2020). The top-down approach is composed of physical methods, while bottom up approach is composed of biological and chemicals methods. The top-down approach is composed of physical methods, while the bottom-up approach is composed of biological and chemical methods (Altammar, 2023). In top-down approaches, bulk materials are mechanically converted into nano-sized fine particles, conversely, the bottom-up approach involves the self-assembly or co-precipitation of fine particles to produce nanoparticles (Paramasivam et al., 2021).

CHALLENGES IN NANOMEDICINE

Efficacy of Nanomedicine in Drug Delivery

Nanomedicine has demonstrated significant potential in all aspects of pharmaceutical treatment, presenting a wide range of advantages that can enhance the effectiveness and safety of medicinal therapies (Parveen et al., 2017; Sahoo et al., 2017). Nanoparticles, liposomes, and other carriers at the nanoscale have the capability to be deliberately designed for the purpose of delivering medications in a targeted manner, hence reducing the occurrence of unintended consequences. Nanocarriers can also enhance the stability and bioavailability of inadequately water-soluble drugs (Singh, 2009). Nanoparticles can be created to release drugs over an extended period, resulting in a sustained therapeutic effect, and can enhance the cellular absorption of drugs, including those that would ordinarily have difficulty penetrating cell membranes (Anselmo & Mitragotri, 2016; Liu, Zhao, & Li, 2022). These are particularly advantageous for chronic conditions requiring continuous drug administration and the treatment of intracellular infections or diseases such as cancer (Jin et al., 2019). Nanomedicine has the potential to facilitate the circumvention of diverse biological barriers, such as the blood-brain barrier (BBB) or the mucus barrier inside the respiratory system, therefore enabling medications to effectively rich their designated targets (Tam et al., 2016). Recent research has provided evidence that several kinds of Carbon Dots (CDs) and CD-ligand conjugates have shown effective penetration of BBB. This finding implies a significant ad-vancement in the potential use of CD-based drug delivery systems for the treatment of central nervous system (CNS) illnesses (Zhang et al., 2021). By delivering pharmaceuticals directly to affected tissues or cells, nanomedicine may reduce exposure of healthy tissues to the drug, thereby minimizing adverse effects and toxicity (Chauhan & Jain, 2013).

Potential Side Effects and Safety Concerns

Nanomedicine and drug delivery systems offer a variety of advantages, but there are also potential adverse effects and safety concerns. Due to their minuscule size they can more easily penetrate the human body than larger particles (Bamrungsap et al., 2012). Nanomaterials, cross-linkers, and other reducing agents that are frequently used in the formulation of namomedecines have a number of adverse consequences (Lam et al., 2017). The induction of reactive oxygen species by quantum dots results in cytotoxicity, which damages the mitochondria, nucleus and plasma membranes. It has been reported that quantum dots containing cadmium (Cd) are toxic due to the discharge of free Cd2+ ions (Kirchner et al., 2005). Only concentrations above 0.1 mg/ml of silica nanoparticles were found to be toxic, as evidenced by a decrease in cell availability and proliferation (Chang et al., 2007). Studies conducted both in vivo and in vitro have shown that the reported mild toxicities associated with nanoparticles may be attributed to the elevation of reactive oxygen species (ROS) levels (Khanna et al., 2015). The maximum formation of reactive oxygen species is seen while using amorphous TiO2 nanoparticles with a diameter of 30 nm and silver nanoparticles with a diameter of 15 nm. The potential absorption of silver nanoparticles and quantum dots by macrophages significantly enhances the production of inflammatory mediators, including TNF-α, MIP-2, and IL-1β, regardless of the particles' size (Albanese et al., 2012). For numerous impacts their possible side effects and safety issue should be assessed. There is a need for the implementation of green synthesis techniques, as well as the creation of standardized reference materials

Another regulatory hurdle is the determination of appropriate risk-benefit ratios for nanotechnology-based therapies. Since nanomedicine products often offer unique therapeutic benefits, regulators must carefully weigh these benefits against potential risks to ensure patient safety (Poirot-Mazères, 2018). This process requires robust scientific evidence from preclinical and clinical studies, as well as comprehensive risk assessments.

In addition to safety considerations, regulatory approval also hinges on demonstrating the efficacy of nanotechnology-based therapies. This entails conducting rigorous clinical trials to evaluate the therapeutic outcomes and patient outcomes associated with these therapies. However, designing and conducting clinical trials for nanomedicine products present unique challenges, such as patient recruitment, sample size calculations, and endpoint selection. Despite these challenges, regulatory agencies are making strides in adapting their regulatory frameworks to accommodate nanotechnology-based products. Collaborative efforts between regulatory agencies, industry stakeholders, and academic researchers are essential for overcoming regulatory hurdles and ensuring timely approval of safe and effective nanomedicine therapies (Halamoda-Kenzaoui, 2022).

In conclusion, navigating the regulatory landscape for nanotechnology-based products requires careful consideration of ethical principles, scientific evidence, and regulatory requirements. By addressing ethical considerations and overcoming regulatory hurdles, we can harness the full potential of nanomedicine to improve healthcare outcomes and enhance patient well-being (Germain, 2020).

THERAPEUTIC APPLICATION

Therapeutic Application of Nanomedicine in Cancer Therapy

Nanomedicine presents a leading-edge approach to cancer therapy by utilizing nanoparticles for accurate diagnoses and treatments (Xu, Han, Xiong et al, 2023). Nanoparticle-mediated drug delivery, which involves passive and active targeting techniques, has been investigated to overcome difficulties including drug resistance, insufficient solubility, tumor targeting issues, early detection, metastasis, lack of targeted therapies, systemic toxicity, and relapse (Jaggi & Joshi, 2017). Adjuvant nanomedicine has been utilized for improving conventional medicines including surgery, gene therapy, chemotherapy, immunotherapy, and radiotherapy, by providing customizable physicochemical properties and specific disease targeting, consequently boosting therapeutic results (Xu, Hsu, Xu et al, 2023). Two aspects of cancer immunotherapy are TME modulation and cancer vaccinations (Zhu et al., 2022). Palladium, gold, silver, and platinum are examples of functionalized metallic nanoparticles that have been investigated for their potential to boost the impact of drug delivery, antibody specificity, photothermal and photodynamic treatment, and other therapies on cancer cells (Montazersaheb et al., 2023). The latest advances in situ self-assembled nanotechnology have demonstrated possibilities for multimodal therapy, tumor imaging, and highly effective cancer treatment (Sun et al., 2023). These groundbreaking developments in nanomedicines offer novel opportunities for the treatment of cancer, with the objective of enhancing patient survival and minimizing adverse effects (Narayana, 2014).

osteoporosis, etc. (Doroudian et al., 2023; Kaur, Nagpal, & Aggarwal, 2022). Nanotechnology in medicine has numerous potential applications in a broad range of areas, including cardiovascular disorders and stroke, drug delivery, bio-imaging, and the improvement of nano-scale devices and sensors (Kim et al., 2011). Pain-relieving nanoparticles provide targeted and long-lasting therapeutic benefits, and advances in inhalable nano-formulations for pulmonary disorders offer more effective treatment outcomes (Taghavizadeh Yazdi et al., 2023). These developments demonstrate how profoundly nanomedicine can impact specialized medical fields, breaking through barriers to change treatment paradigms.

CASE STUDIES

Application of Nanomedicine in Cancer Treatment

Nanomedicine has demonstrated insignificant potential in the field of cancer treatment through the provision of novel approaches for diagnosis, drug administration, and therapy (Kateb et al., 2011). By engineering nanoparticles, chemotherapeutic drugs and other therapeutic agents can be delivered directly to cancer cells while sparing healthy tissues (de Lázaro & Mooney, 2021). Nanoparticles can encapsulate these drugs, enhancing their solubility and bioavailability and controlling drug release which can reduce fre-quent dosing of drugs. Anthracycline antibiotic doxorubicin (DOX) inhibits DNA and RNA synthesis, topoisomerase II (TOP2), and produce free radicals, causing oxidative damage to DNA and proteins. This chemotherapy is highly effective for various cancers, including acute lymphoblastic leukemia (ALL), acute myeloblastic leukemia (AML), Wilms' tumor, neuroblastoma, soft tissue and bone sarcomas, breast, ovarian, transitional cell bladder, thyroid, gastric, Hodgkin's, malignant, and bronchogenic carcinomas. Although DOX has potent anticancer effects, may cause side consequences like as cardiotoxicity and myelosuppression. Liposome formulated DOX was approved by the FDA as Doxil in 1995 to decrease side effects and boost efficiency and being as the first nanomedicine for cancer (Norouzi et al., 2020). Mifamurtide liposomeal formulation is a nonspecific immunomodulator that induces the secretion of inflammatory cytokines and the activation of monocytes and macrophages, thereby upregulating tumori-cidal activity (Biteau, 2016). Similar to these previously mentioned drugs, Human serum albumin NPs, Liposome (POPC, OOPS), Liposome (sphingomyelin, cholesterol) and Liposome (DSPC, cholesterol and mPEG-DSPE) are used in the formulation of PTX, mifamurtide, Vincristine sulfate, and Irinotecan, respectively, to increase drug activity and decrease unintended effects during cancer therapy. In addition, phase II and phase III trials for other nanomedicines are being conducted for the treatment of cancers (Bedikian et al., 2006; Desai, 2016; Pillai, 2019).

Nanotechnology for Targeted Delivery in Infectious Diseases

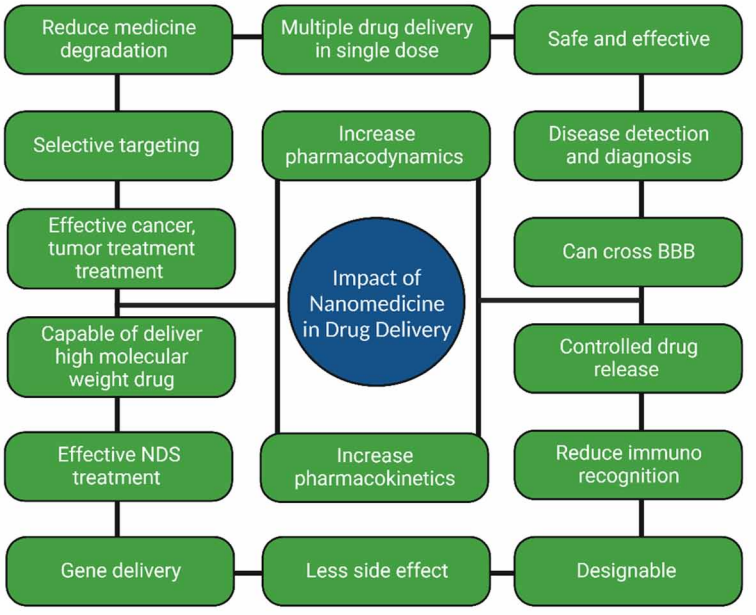
The global spread of infectious diseases caused by bacteria, viruses, and fungus poses a significant risk to human health. Nanoparticles (NPs) have notable antibacterial efficacy via the release of reactive oxygen species and metal ions, as well as by inducing photothermal effects and disrupting the integrity of the cell membrane. The use of nano-based delivery systems has the potential to enhance drug permeability, mitigate the adverse effects of medications, and extend the duration of systemic circulation and drug half-life (Liu et al., 2021).

and promote neuronal differentiation and neurite outgrow (Kumar et al., 2020). Curcumin-encapsulated PLGA nanoparticles (Cur-PLGA-NPs) AuNPs loaded with 6-mercaptopurine (anti-inflammatory drug) which functionalized by RDP (neuron-targeting peptide) are also promote neurite growth and cell proliferation (Binda et al., 2020; Rai & Yadav, 2019). Peptide-tagged polyethylene glycol- (PEG-) related chitosan polymer can deliver a functional siRNA against the Ataxin-1 gene activity of ND (Kassem, 2020). Likewise, Nano encapsulation mediated drug delivery system can transport antibodies inside the brain to treat ND (Kassem, 2020). Nitrendipine and nilvadipine are reduce around 55% of dementia by blocking calcium's uncontrolled influx into the neurons (Binda et al., 2020).

Success Stories Illustrating the Impact of Nanomedicine in Drug Delivery

From the beginning, the expansion of nanomedicine has been upward (Binda et al., 2020). Nanomedicine is a state-of-the-art technology, bringing about a revolution in drug delivery. Nanomedicine currently archive the ability of diagnose and treat disease simultaneously (Patra, Das, Fraceto, Campos, Rodriguez-Torres, Acosta-Torres, Diaz-Torres, Grillo, Swamy, Sharma, Habtemariam, & Shin, 2018). Precise treatment, reduced off-target effects, and effective cellular targeting capabilities are now a reality due to nanomedicine (Mitchell,, 2021). Nanomedicine offers better cancer diagnosis and treatment (Germain et al., 2020).

Figure 3. The impact of nanomedicine in drug delivery



Exploration of Emerging Nanotechnologies for Drug Delivery

Emerging nanotechnologies offer exciting opportunities for advancing drug delivery beyond conventional nanoparticle-based systems. Researchers are exploring alternative nanomaterials, such as carbon nanotubes, graphene, or metal-organic frameworks, for drug delivery applications. These materials exhibit unique physicochemical properties that may offer advantages in terms of drug loading capacity, stability, or stimuli-responsive behavior (Mitchell, 2021).

Furthermore, the integration of nanotechnology with other disciplines, such as synthetic biology, microfluidics, or artificial intelligence, opens up new avenues for innovation in drug delivery systems (Liu, 2021). By harnessing the power of interdisciplinary collaboration, researchers can develop next-generation drug delivery platforms with enhanced functionality, precision, and therapeutic efficacy.

In conclusion, the future of nanomedicine holds immense promise for revolutionizing drug delivery systems and improving healthcare outcomes. By leveraging ongoing research and innovation, we can expect to see safer, more efficient, and personalized nanomedicine-based therapies that address the unmet medical needs of patients worldwide.

COLLABORATIVE EFFORTS AND PARTNERSHIPS

Collaboration lies at the heart of innovation in nanomedicine, bringing together diverse expertise and resources to address complex healthcare challenges. Interdisciplinary collaboration fosters synergy between different fields, accelerates scientific discoveries, and translates research findings into tangible clinical applications. In the realm of nanomedicine, collaborative efforts among researchers, clinicians, industry partners, and regulatory bodies play a pivotal role in driving progress and facilitating the development of novel therapeutic interventions (Zhang, 2020).

Importance of Interdisciplinary Collaboration in Nanomedicine

Nanomedicine represents a convergence of multiple disciplines, including nanotechnology, medicine, biology, chemistry, engineering, and materials science. Each of these disciplines contributes unique perspectives and methodologies to the field, enabling the design, synthesis, and characterization of nanoscale materials for biomedical applications. Interdisciplinary collaboration promotes cross-fertilization of ideas, fosters innovation, and pushes the boundaries of scientific knowledge (In Praise of Interdisciplinary Science, 2022).

For instance, engineers may design nanocarriers with precise control over size, shape, and surface properties, while biologists elucidate the biological mechanisms underlying disease progression and drug action. Clinicians provide essential insights into clinical needs, patient care pathways, and therapeutic efficacy, guiding the translation of nanomedicine from bench to bedside. By bridging disciplinary boundaries, interdisciplinary collaboration enables holistic approaches to healthcare challenges and facilitates the development of patient-centered solutions.

medicine, tailored interventions now consider individual genetic variations, metabolism, and disease progression.

In the past decade, the nano pharmaceutical industry has witnessed significant growth and development, driven by the advantages of nanotherapeutics in pharmacokinetics, efficacy, and safety. Thriving nano-therapeutical research is evident in the increasing number of publications in nanomedicine, offering innovative solutions to longstanding challenges and enabling more effective, targeted, and personalized therapeutic interventions.

Advancements in drug delivery systems in recent years have greatly improved automation, efficiency, and precision, enabling drugs to reach specific target areas while minimizing systemic exposure. Traditional methods often fail to achieve regulated drug release, but micro-electro-mechanical systems (MEMS) offer precise control. Nanoparticles show promise in delivering combination medicines for cancer treatment and overcoming drug resistance. Ongoing research should focus on the toxicity, efficacy, and biocompatibility of nanotherapeutics, while continuing to enhance drug delivery systems for improved patient outcomes.

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