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REVIEW ARTICLE

Nanotechnology-Enabled Precision Drug Delivery: Revolutionizing Therapeutic Strategies for Health and Disease

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Abstract: Drug delivery is undergoing a radical transition thanks to nanotechnology, assist in an era of more precision and fewer adverse effects. Nanotechnology is being a revolutionary approach that enables regulated drug release and targeted delivery while protecting healthy tissues, hence minimizing negative effects. Therapeutic chemicals are encapsulated within nanoparticles and nanocarriers. The use of nanotechnology in the treatment of cancer stands out as a noteworthy accomplishment. Nanotechnology has enormous potential for treating a wide range of illnesses, including autoimmune disorders, infectious diseases, and neurodegenerative ailments, in addition to oncology. Its precise management of medication distribution creates new therapeutic opportunities. For instance, tailored nanoparticles can cross the formidable blood-brain barrier, gaining access to parts of the central nervous system that were previously unreachable. Nanotechnology can be precisely tuned to target microorganisms in the context of treating infectious diseases, perhaps leading to more effective and non-toxic antimicrobial therapies. Additionally, in autoimmune illnesses, nanoparticles can be extremely important in controlling the immune response, resulting in more tailored and efficient treatment plans. The blending of diagnostic technologies and nanotechnology has resulted in a revolution in personalized treatment. Nanotechnology is being applied in the domains of food and dietary supplements. It is causing a paradigm change in drug delivery methods because it offers personalised, effective, and targeted therapies with little side effects. As this field of inquiry advances, there is excitingly hopeful future potential for revolutionary nanoscale medicine delivery methods that can further improve healthcare and overall welfare.
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Keywords: Nanotechnology; Drug delivery; Targeted therapy; Encapsulation; Personalized medicine

1. Introduction

Nanoparticles are colloidal, sub-nanometer-sized structures made of synthetic or partially synthetic polymers [1]. The scientific field of nanoscience, also referred to as nanotechnology, studies materials at the atomic or molecular level. In other words, the phrase "nanotechnology" refers to the investigation, design, fabrication, synthesis, manipulation, and application of materials, processes, and structures at a scale of 1–100 nanometers (nm) [2]. A new area termed nanomedicine has emerged as a result of a growing interest in the medical uses of nanotechnology. The term "nanomedicine" refers to the application of nanobiotechnology to the field of medicine. It is based on the use of nanoscale materials and devices for drug delivery, diagnosis, and the creation of novel medications known as "nano pharmaceuticals [3]. Modern nanotechnology is emerging as a potentially revolutionary branch of research that can transform several industries, including healthcare, as a result of these special characteristics of nanomaterials. In light of recent developments in the field of nanotechnology, it is clear that this technology has an impact on practically every aspect of modern life, from security to medicine. Most people believe that nanotechnology and its medical applications have a huge potential to advance numerous fields of investigation and applications. The diagnosis, drug administration, and treatment of a wide range of illnesses, including several serious and life-threatening diseases like cancer, neurodegenerative disorders, cardiovascular diseases, etc., are currently made possible by nanotechnology thanks to wholly unique concepts and methods. Because of their physical stability, ability to protect incorporated labile drugs from degradation, controlled release, and excellent tolerability, solid-lipid nanoparticles have attracted considerable interest from a variety of researchers since the mid-1990s as a novel carrier system for drug delivery applications. These lipid-based submicron particles, which are solid at both room temperature and body temperature, range in size from 50 to 1000 nm. The spherical biodegradable solid lipid nanoparticles that are most frequently utilised are formed of proteins (such as albumin or collagen), lipids, or polymers. Solid lipid nanoparticles can be delivered orally, parenterally, topically, ocularly, pulmonaryly, duodenally, and rectal route [4,5].

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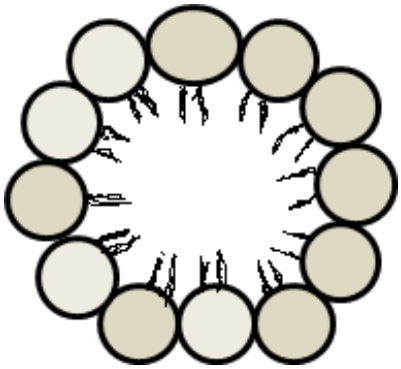

Figure 1 Structure of Solid Lipid Nanoparticles (SLNs)

2. Solid Lipid Nanoparticles (SLNs)

Cancer cells are made up of microscopic cells that are unable to stop growing and can originate from any organ or part of the body. The body's immune cells' incapacity to recognise and eliminate the newly generated cancer cells while they are small in number is likely more important in the development of cancer than the transformation of a normal cell into a malignant cell..[10] In the past 50 years, there has been significant progress in both cancer detection and therapy. Cancer, the "C-word," used to be a death sentence. Although there are many cancers that we can treat and cure today, it is obvious that these diseases must be discovered early. The cancer in over seven out of ten youngsters is cured. Adult patients can benefit from current therapies for Hodgkin's lymphoma, testicular cancer, and many types of leukaemia. Surgery is used to treat most skin malignancies. Furthermore, radiation therapy is a successful treatment for many cases of laryngeal and thyroid cancer. If detected in time, many other cancers can also be treated; for instance, 75% of breast tumours are curable when detected in their early stages. Naturally, there is still a long way to go before many tumours are cured. One technique cannot prevent all cancers since they are caused by multiple factors, which presents a challenge. Additionally, various therapies work on each, thus no single therapy is effective for all of them. Even while nanotechnology is thought to be a potential therapy for several malignancies, including ovarian cancer. [11]

3. SLNs in Cancer treatment

Lipid-based nanocarriers provide significant promise in terms of solubilizing, encasing, and delivering active molecules in a predetermined manner to attain bioavailability and prevent adverse reactions. An important new field uses these carriers to transmit immunological signals and peptides (antigens) that the immune system recognises to control the immune response.[6]This development is motivated by the unique benefits of polymeric carriers and other designed materials in the context of immunotherapy, including co-delivery of immune signals, controlled release, prolonged cargo exposure, cargo protection, and preferential delivery to target immune cells.[7] The distinct advantages of polymeric carriers and other engineered materials in the context of immunotherapy—such as the ability to co-deliver immune signals, control release, expose cargo for an extended period of time, protect cargo, and deliver immune cells preferentially to target—are what drove this development.[8] Lipid-based carriers provide crucial characteristics that allow for rate-controlled release rate modulation, increased blood-brain barrier penetration, and circumvention of the hepatic first-pass metabolism, resulting in increased CNS bioavailability of neurotherapeutics. The limits of neurotherapeutics, pharmacological barriers, difficulties with brain-targeted distribution, and the promise of lipid-based carriers processed by nanotechnology in the clinical treatment of neuronal illnesses are briefly and briefly discussed in the current study.[9]

3.1 Ovarian cancer: Globally, ovarian cancer (OC) is the seventh most common cause of death for women. The American Cancer Society estimated that there will be 14,070 fatalities and around 22,240 new cases in the US in 2018.[12] Fifty to seventy-five percent of advanced-stage cancer patients who react well to current therapy later relapse. The primary cause of early-stage ovarian cancer's delayed diagnosis—which typically happens at a metastatic stage, significantly decreasing the likelihood of a good treatment outcome—is its asymptomatic character.[13] Because routine early detection procedures are not available, OC-associated death rates are high even with ongoing advancements in screening techniques. The diagnostic procedure is made more difficult by the limited specificity of the tests that are now available and the restrictions on the use of imaging methods.[14]

3.1.1. Treatment of ovarian cancer: The fabrication of metal nanoparticles including iron gold, silver, and metal oxide nanoparticles has received intense attention in recent years for the treatment of ovarian cancer. The synthesis and modification of the metal nanoparticles are dependent on shape, size, and target accumulation to develop an effective nanotechnology approach. Among the nanoparticles, iron-oxide nanoparticles (Fe2O3 NPs) as illustrated in Figure 2 appear a prospective kind of candidates in contemporary nanobiotechnology for a wide spectrum of applications such as antioxidant, antibiofilm, antimicrobial, and anticancer activities.[15] The medications of interest are contained inside the inner core chamber of nanocapsules, which are tiny

vesicular structures. An outer shell polymer membrane encloses the center core and serves as a surface for the attachment of targeted ligands or antibodies attached to the surface.[16] These worries can be allayed by using nanomaterial-based biosensors, which have higher selectivity and sensitivity. Furthermore, the majority of nanosensors are involved in laborious, complicated processes that frequently fail to offer a clear method of assessing biomarkers, even in cases when they produce useful analytical data. Magnetoresistive, electrical, or electrochemical sensors offer a multitude of advantages in addressing this. Lastly, research on portable sensors to be utilised for ovarian cancer biomarker detection outside of the clinic is still quite limited. The biosensing platform must be integrated into the system at the system level, which is still in the early stages, in order to market the biosensors. In order to address it, current efforts are being made to create low-cost, reusable biosensors based on paper, flexible FET forms, GMR, or lab-on-a-chip systems based on microfluidics.[17-20]

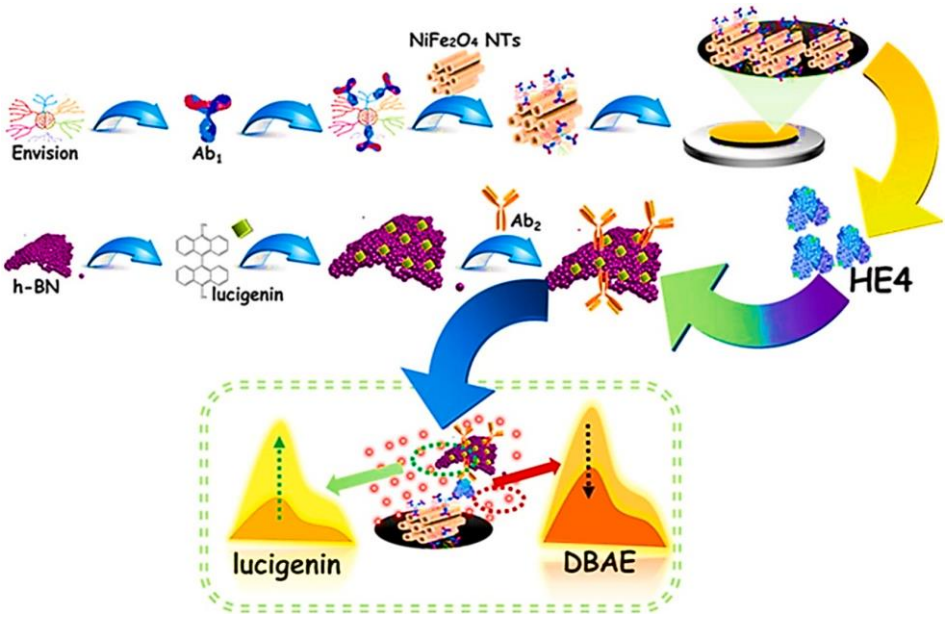

Figure 2 Diagrammatic representation of the electrochemiluminescence nanosensor based on NiFe2O4 nanotubes for the detection of HE4 as an ovarian cancer biomarker.[21]

4. SLNs in treatment of autoimmune disorders

Biomaterials are becoming more and more crucial as delivery vehicles for immunotherapies as they become more individualized and patient-specific to enhance patient outcomes.[22] Because biomaterials are extremely customizable and have features that can be tailored to satisfy a wide range of tasks, they provide remarkable flexibility in stabilizing and delivering therapeutic cargo.[23] The excipients added to improve storage must allow immune cargo bio functionality and not interfere with drug-target interaction in order to preserve the advantages of biomaterial-based immunotherapy. In comparison to Rapa MPs, empty MPs showed greater levels of activation during DC culture assays, both before and after lyophilization and storage. When IL-6 secretion was measured, this was likewise observed in many instances. This might be the consequence of the polymer's immunogenic qualities or the degradation of the polymer—PLGA is known to exhibit some inherent immunogenicity during its degradation.[24]

5. SLNs in treatment of infectious diseases

In the realm of vaccination, researchers are looking at the use of nanoparticles as new adjuvants and nanoemulsions as colloidal vaccine carriers. The potential of calcium nanoparticles as a vaccine adjuvant for anti-idiotypic antibodies against schistosomiasis has been investigated.[25] A vast range of illnesses are being prevented and treated with the use of nanoemulsions, which are made up of tiny oil droplets floating in water and stabilized by detergents. Because they are surface active, droplets in nanoemulsions selectively interact with the outer membrane of infectious organisms. Combinations of the nanoemulsion with either the entire virus or the protein have been explored as possible vaccines in pre-clinical studies conducted on animals at the University of Michigan. These vaccinations, which are not necessary cold storage and the mucosal method of administration make it especially appropriate for use in underdeveloped nations. Using the hazardous characteristics of metal oxides and nanoparticulate metals—especially those that generate reactive oxygen species when exposed to UV light—in antimicrobial compositions and dressings both inside and outside of hospitals is becoming more and more common. Many studies have been conducted on compounds containing silver and copper. Specifically, most microbes, including HIV-1, have been shown to be rendered inactive by nano silver particles (5–40 nm). For their bactericidal properties, titanium dioxide and silicon dioxide's strong reactivity are widely used in filters and coatings on

substrates like alumina.[26] Nanotechnology is being used to diagnose infectious illnesses more quickly by taking use of its larger functional surface area per unit volume. Biosensors are being developed as devices where a biological sensing element is either incorporated into a transducer or is closely coupled to it. These biosensors are composed of nanofabricated structures covered with biomolecule-adherent materials like gold. With the use of such an approach, a quick technique for the diagnosis of urinary tract infection caused by E. coli has been established, for instance. [27]

6. Nanotechnology impact on food and dietary supplement

Nanoemulsions are kinetically stable liquid-in-liquid dispersions with droplet diameters less than 200 nm. The two incompatible liquids that are used in business settings the most are water and oil. Due of their tiny size, they frequently exhibit qualities like adjustable rheology, large surface area per unit volume, sound stability, and visual transparency. Furthermore, it is not difficult to prepare large-scale nanoemulsions in industrial settings. As a result, nanoemulsions are particularly well suited for industrial uses. Nanoemulsions are kinetically stable liquid-in-liquid dispersions with droplet diameters less than 200 nm. The two incompatible liquids that are used in business settings the most are water and oil. Due of their tiny size, they frequently exhibit qualities like adjustable rheology, large surface area per unit volume, sound stability, and visual transparency. Furthermore, it is not difficult to prepare large-scale nanoemulsions in industrial settings. As a result, nanoemulsions are particularly well suited for industrial uses. [28-30] The generally utilised methods for producing nanoemulsions include low-energy techniques (e.g., SE and PIT/PIC) and high-energy approaches (e.g., RSE, HPH, HPMF and USH) (e.g., RSE, HPH, HPMF and USH). Because they are thermodynamically unstable, nanoemulsions usually degrade during storage as a result of a number of physical processes, including creaming, flocculation, coalescence, and Ostwald ripening. Moreover, nanoemulsions may degrade over time as a result of a variety of chemical or biological processes, most notably lipid oxidation, or they may lose the properties that make them palatable. Thus, enhanced physical stability (e.g., adding appropriate stabilisers, such as texture modifiers, emulsifiers, weighing agents, and ripening inhibitors) and chemical stability should be carefully considered when designing nanoemulsions (e.g., by adding antioxidants). Researchers have encapsulated active ingredients in nanoemulsions for a long time.[31]

7. Conclusion

In conclusion, this study underscores the transformative potential of nanotechnology in healthcare. "Nanomedicine" is ushering in a new era of precision medicine, with a primary focus on drug delivery, diagnostics, and novel pharmaceuticals. Solid lipid nanoparticles, together with other carrier materials, offer promising solutions to the challenges of medication stability, controlled release, and patient tolerability. They have demonstrated significant potential for targeted drug delivery, especially in immunotherapy. Nanotechnology's broad applications extend to treating various diseases, including infectious diseases, cancer, and autoimmune disorders. Metal nanoparticles, like iron-oxide nanoparticles, exhibit promise in addressing diseases such as ovarian cancer, while nanoemulsions serve as effective vaccine carriers for infectious diseases.

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