Innovative Applications of Smart Materials in Precision Medicine

Jieying Lyu *

School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou, Guangdong, 510006, China

* Corresponding Author Email: 3222001678@mail2.gdut.edu.cn

Abstract. Improving healthcare is a worldwide concern, and in recent years attempts have been made to introduce nanotechnology and nanomaterials into the healthcare system to solve its problems. The small size and high surface area of nano make it much more usable. This paper focuses on the advantages of nanomaterials and how they can be used in precision medicine and presents the remaining problems of nanomaterials in healthcare. Also, the paper concludes by suggesting possible future applications of nanotechnology in the healthcare system. Through this paper, the advantages of inorganic nanomaterials, such as gold nanoparticles and silver nanoparticles because of their antimicrobial and anti-inflammatory properties in healthcare, and the biocompatibility of organic nanomaterials, such as liposomes, which makes them useful in transporting drugs, are derived, and then the advantages of both are combined to design hybrid nanomaterials and apply them. There is also a summary of specific application scenarios for nanomaterials, such as precision drug delivery, regenerative medicine, and vaccine development, as well as future application directions. Throughout the paper, the authors believe that the integration of nanotechnology into precision medicine is a major trend and that healthcare continues to progress due to its advantages. However, it is necessary to consider the toxicity and biocompatibility of nanomaterials, which will require more research and testing in the future.

Keywords: Nanomaterials; Smart Materials; Precision Medicine.

1. Introduction

Healthcare is a growing concern with the advancement of technology, and the utilization of advanced technologies to enhance healthcare is a global concern. Nanomaterials, which are usually between 10-200 nm in size, have high surface energy and multiple reactive sites, allowing them to exhibit higher catalytic activity in chemical reactions. For example, gold nanoparticles exhibit excellent performance in catalytic reactions, whereas macroscopic gold nuggets exhibit little to no catalytic activity. Nanomaterials also have a dynamic response mechanism, which refers to their ability to undergo structural or property changes in response to external stimuli (e.g., pH, temperature, enzymes, etc.) to realize specific functions.

Previously, the main problems were the lack of significant antimicrobial and anti-inflammatory properties of the drug, the lack of biocompatibility of the bone implanted in the human body and the problem of vaccines. However, in recent years, nanotechnology has been developing at a high-speed. People have discovered many inorganic nanomaterials (gold nano, silver nano) and organic nanocarriers (liposomes) and combined them to form nanosystems. For example, silver nanomaterials have good antimicrobial, antiviral, and anti-inflammatory properties, and by attaching certain carriers, the best properties of each can be utilized and exploited [1]. The discovery of these materials has applications in precision medicine, such as regenerative medicine, vaccine development and precision drug delivery (targeted tumor therapy). For example, making bionic bone from bioceramics and composite nanostructured biomaterials facilitates bone repair treatment in the human body [2]. This is undoubtedly an innovation and enhances the treatment of human diseases. In addition to this, future innovative applications of nanomaterials in precision medicine include personalized nanomedicine, bionic nanorobots and organ-on-a-chip integration technologies. However, this still requires a lot of research and testing, and attention needs to be paid to the composition, biocompatibility and structure of these smart materials.

This paper discusses nanotechnology and nanomaterials in precision medicine by analyzing the structural characteristics of three nanomaterials (inorganic nanomaterials, organic nanomaterials, and hybrid nanosystems). Nanotechnology and nanomaterials remain an evolving process, and researchers need to continue to explore their potential and integrate them with human needs in order to develop more precise drug delivery systems and improve the ability to treat disease.

2. Classification of Nanomaterials

2.1. Inorganic Nanomaterials (Gold Nanoparticles and Silver Nanoparticles)

In medicine, gold nanoparticles have been used for decades, initially for the treatment of arthritis. They have been combined with other substances (e.g., chondroitin sulfate) to enhance their therapeutic effects and, because they are non-toxic, can also be used to deliver drugs and genes. In addition, gold nanoparticles are also used in the treatment of tumors by irradiating them with the appropriate light so that the gold nanoparticle reaches its maximum absorption in the visible or near-infrared region. It absorbs light energy and converts it into heat to be delivered to the surrounding environment, thus killing the cells around and inside the target cells to achieve the effect of treating tumor diseases, which is classified as photothermal therapy. Because of its stable structure and low toxicity, the color of gold nanoparticles changes depending on the size, so it is also possible to detect cancer, and the size can be changed during the detection process. In detecting cancer, especially cancer cells throughout the body, gold nanoparticles are used for imaging because of their color-changing properties. Their good absorption coefficient and body tolerance are less harmful to the human body than conventional X-ray based CT machines [1]. The use of other substances (e.g., antibodies) can be used as contrast agents for tumor imaging. In addition to this, functionalizing gold nanoparticles can be used to detect cancer by detecting proteins, antibodies and disease markers and binding to them to release signals. Researchers are therefore using them in nanobiosensors to diagnose cancer. Gold nanoparticles also played a big role during the New Crown outbreak and were also used in testing kits because of their color-changing properties. This is a molecular level test that detects a person's RNA thus recognizing the virus and determining if a person is positive and infected. It reduced the testing time for individuals and allowed individuals to test themselves for infection during the big outbreaks of the time, providing a more convenient and rarely contacted method.

Silver nanoparticles have excellent antibacterial, antiviral and anti-inflammatory properties. It is an antimicrobial agent whose antimicrobial effect depends on the shape, size and concentration of the nanoparticles. Studies have shown that the larger the surface area, the higher the antimicrobial activity. However, long-term use of antifungal drugs can lead to the development of resistance in fungi. Therefore, AgNPs exert their antifungal effects by disrupting cell membranes and inhibiting the normal process of asexual reproduction. When silver nanoparticles are used as antiviral drugs, they act directly in contact with the proteins on the surface of the virus and will reduce the infection of cells by the virus. In addition, when silver nanoparticles are used as an anti-inflammatory agent, it was concluded that silver nanoparticles can reduce inflammation through injection experiments on albino white rats, which resulted in silver nanoparticles inhibiting edema [1]. Apart from these, it can also be used as an antiplatelet agent and an antiparasitic agent.

2.2. Organic Nanocarriers (Liposomes)

In previous studies, researchers have conducted an in-depth study on lipid-based nanoparticles (a type of carrier), which is considered safe because it is biocompatible. Lipid nanoparticles are one of the categories that have many uses, such as probes for magnetic resonance imaging, near-infrared fluorescence imaging, and components of mRNAs in new crown vaccines. In vaccines, it protects and transports the mRNA to the cell. The most common morphology of lipid-based nanoparticles is a vesicle-like spherical platform of water encapsulated by at least one lipid bilayer, so it has transport functions such as the delivery of hydrophobic and hydrophilic drugs (e.g., vaccines, insulin, proteins, etc.). It can also modulate physicochemical properties and thus alter biological properties. Liposomes are also a class of lipid-based nanoparticles. It is much like a cell membrane, a vesicle-like layer or layers of phospholipids. It has good drug delivery properties, biocompatibility and biodegradability due to the principle of similarity and compatibility, which makes the drug more stable in transit [2].

2.3. Hybrid Nanosystems

Hybrid nanosystems are nanocomposites composed of at least two different types of materials. By utilizing the advantages of hybrid and synergistic materials, the disadvantages of a single material are overcome thereby creating nanostructures with unique properties. It has been used to prepare photostimulation-responsive drug carriers for the treatment of cancer in combination with chemotherapy and photochromic therapy. In addition to this, it has also been made into pH-responsive liposomes for applications in skin drug delivery systems. In addition, although silver nanoparticles have antimicrobial activity and can be used as disinfectants, at the same time they are toxic, so they are encapsulated in biocompatible systems such as liposomes and silica nanoparticles. Researchers are working to put silver nanoparticle liposomes into a wide range of applications, such as in antimicrobial and antioxidant systems, as target active agents for cancer and arthritis and to protect healthy cells [3].

3. Innovative Applications of Nanomaterials in Precision Medicine

3.1. Precision Drug Delivery

Previous drugs suffered from poor solubility, poor absorption in the body and poor sustained efficacy. Nanomaterials have a high surface area-to-mass ratio, quantum properties, and the ability to adsorb and transport drugs and other compounds. Therefore, engineering nanomedicines allows for precise drug delivery by encapsulating the drug or adsorbing it. Because of their small size, they can well enable the drug to enter the tissue system, thus facilitating cellular uptake of the drug, and ultimately allowing the drug to exert its effects at the target location for efficient drug delivery. In addition, researchers have found that incorporating nanoparticles into the original drug compounds can significantly improve the properties of these compounds, such as bioavailability and targeting.

However, the study indicated that systemic drug delivery using nanoparticle materials was inefficient, with only 5% reaching the central system and less than 5% reaching the target cells. This is mainly due to many problems in the delivery process such as biological barriers, environmental barriers and mucus permeation problems. Firstly, biological barriers have problems with shear stress, protein adsorption and rapid clearance. These issues are difficult to address uniformly and broadly because these types of physiological and biological barriers differ in each individual. Regarding the rapid clearance problem, for example, the kidneys excrete nanoparticles with a diameter of less than 10 nanometers, and researchers modulate the physicochemical properties of the nanoparticles so as to minimize this problem. The researchers also polyethylene glycolized the nanoparticles, thereby extending the nanoparticle circulation time and reducing the likelihood of nanoparticle degradation and rapid removal. The polyethylene glycol was coated onto the nanoparticle formulations to achieve stealth. Such a surface modification approach could allow for longer circulation times, more structural stability and reduced in vivo clearance of nanoparticles in the human body. In addition, topical medication can also solve part of this biobarrier problem, but this type of medication has more limitations and can now only be used for certain diseases (diseases that are well-defined and easily accessible) [4]. Therefore, topical medication is still not a substitute for systemic medication.

Secondly, regarding environmental barriers, when the nanoparticles reach the target cell but there are differences in the microenvironment, this can lead to changes in the stability, structure and physicochemical properties of the nanoparticles. For example, the pH in the gut is unstable, acidic and has degrading enzymes and also diseases can change the microenvironment of the gut so this difference in microenvironment can affect the structural stability of the nanoparticles. To solve this problem, researchers have developed PH-responsive nanoparticle drugs so that the drug can be released only at a specific pH value, which can better ensure the use of the drug. In addition to the gut, there are tumor microenvironments and brain microenvironments that can likewise affect nanoparticles [4].

Finally, when it comes to mucus penetration, it is the biofilm and mucus that limits nanoparticles. The length of the links of neighboring polymers in the mucus layer leads to different mesh pores, which results in different passage rates for large and small substances. The mucus traps matter, thus removing the attachment of nanoparticles to the upper surface. The role of mucus is similar, but its characteristics may still vary in different organs, such as the pH and the thickness of the mucus layer, thus affecting the absorption of nanoparticles and their stability. In addition to this, the variability of individual habits and physical conditions can also make the mucus different, causing nanomedicine delivery to become difficult [4].

Considering the precise release of drugs, the researchers designed responsive nanomaterials using a dynamic response mechanism. This is because non-responsive nanomaterials can harm normal tissue cells. In addition, uncontrolled drug delivery during nanodrug delivery can lead to drug release onto normal cells, causing unnecessary harm and reducing pathogen clearance. Therefore, it is essential to design such controlled nanomaterials for precise action and accurate antimicrobials. Stimulus-responsive nanomaterials, i.e., materials that are selectively activated using exogenous or microenvironmental stimuli. Exogenous stimulus-responsive nanomaterials are categorized into light-responsive, ultrasonic-responsive, and magnetic-responsive, all of which absorb the energy of external stimuli and then convert it into reactive oxygen species or heat, etc., so as to achieve the purpose of fighting and eliminating bacteria. As for microenvironment-responsive nanomaterials, i.e., by changing the oxygen concentration, pH value and enzymes, etc., the interaction between microenvironment-responsive nanomaterials and stimuli in the environment is affected, to change the structure, properties and chemical bonding of the materials, etc., and ultimately to achieve the purpose of improving the targeting, antimicrobial and drug-releasing ability of the materials. These two types of stimulus-responsive nanomaterials are only turned on by the corresponding exogenous or microenvironmental stimuli, thus achieving a tunable purpose [5].

3.2. Regenerative Medicine Applications

Bioceramics, metals and nanocomposites have now been introduced in the field of regeneration. Researchers have compared various nanomaterials and found that because of their high stability, tunable structure and large surface area, they promote wound healing in vitro and in vivo, breaking through barriers to injury repair and tissue regeneration. They can mimic the extracellular matrix to catalyze tissue-engineered scaffolds at the nanoscale to achieve enhanced cell adhesion. Regenerative nanotherapeutics because cells have intrinsic defense mechanisms, putting nanomaterials aggressively into cellular environments can promote regular cellular defenses and improve the function of various organelles, thereby reducing or suppressing disease [6]. However, since nanomaterials enter the human body, more research on their toxicity and biocompatibility is still needed.

3.3. Vaccine Development

Nanotechnology can also be used in vaccines to improve and enhance antigen delivery, as well as immunostimulatory adjuvants to induce and enhance protective immunity. Despite the many advantages of traditional adjuvants, they cannot be used in the human body due to their toxicity. Researchers have used nanoparticles (three-dimensional) in far greater amounts than nanofibers (one-dimensional) and nanotubes (two-dimensional) in the development of vaccines. In addition to nanomaterials affecting vaccine development, there is also the material composition of the nanoparticles and the size of the nanoparticles that can have an impact on issues such as transport properties, biodegradability, and efficiency of antigen recognition. First, nanoparticles act as adjuvants and antigens, binding and adsorbing antigens with enhanced antigenicity, thereby mimicking pathogen characteristics and inducing immune responses (including adaptive and innate immune responses). Secondly, nanoparticles have a high specific surface area and act as antigen carriers, processing and presenting antigens to specific tissues and organs, thereby modulating antigen release and targeting cells. In addition to this, nanoparticles can be used as immune enhancers. In conclusion, nanoparticles are now making great strides in vaccine development, but there are still a large number of issues that need to be addressed, such as the tendency of nanoparticles to aggregate, which affects transportation and presentation, as well as concerns about vaccine safety [7].

4. Possible Future Application Directions of Nanomaterials

4.1. Organ Chip Integration Technology

Organic chips allow monitoring of viral infections to understand the development of viruses and potential treatment methods. However, the size of these traditional chips is relatively large, making it difficult to seamlessly place them in microengineering devices and achieve real-time and continuous monitoring. Therefore, researchers hope to solve this problem by utilizing the small size and high sensitivity of nanoparticles. The integration of nanosensors into organoids allows real-time, continuous and in situ monitoring of physiological and pathological changes, leading to better prevention of diseases and more in-depth studies of virology.

There are many types of nanobiosensors such as optical nanobiosensors, piezoelectric nanobiosensors and electrochemical nanobiosensors because of the favorable optical, electrical and mechanical properties of nanomaterials. They have advantages of non-invasiveness, direct detection ability and the ability to analyze concentration information without the need for electrical current, which makes monitoring viruses convenient and direct, overcoming the limitations of traditional materials [8]. In conclusion, nanobiosensors have made a big step forward in studying the dynamic process of viral infections, but subsequent use still requires researchers to improve it experimentally and realize its potential to provide new possibilities for treating diseases.

4.2. Bionic Nanorobotics

Bionic nanorobots combine nanomaterials science and molecular bionics. Researchers hope to design a nanorobot that can affect nanometer-sized objects or spaces. For example, by injecting a nanorobot into the bloodstream, a doctor can monitor changes in the human body and pathogens in real-time without affecting the physiological activities of the human body. If the robot can purify, it can also remove viruses from the body after receiving a report from the doctor [9]. This ability facilitates the treatment of diseases such as kidney and gallstones, where nanorobots can break up the stones inside the body. Nanorobots can also diagnose and treat diseases by releasing drugs for treatment after finding the target pathogen. In short, the development of bionic nanorobots is a major trend, so that can prevent diseases and treat some diseases that are not curable by current medicine.

4.3. Personalized Medicine

The integration of nanomaterials and nanotechnology in personalized medicine will make the level of medical treatment go up another level. Personalized medicine is a kind of treatment that is different and customized for each person, providing the right medicine in the right dosage for the patient's condition and individual situation. First of all, in the diagnostic segment, nanotechnology can realize accurate detection. Secondly, in the therapeutic segment, nanomedicines inappropriate patient doses are targeted and delivered to the cells [10]. However, this is a newly emerging field and more testing is still needed to improve the binding affinity, safety and biocompatibility of nanomedicine.

5. Conclusion

This paper describes the application of nano as a smart material in precision medicine. It elaborates on the antimicrobial and anti-inflammatory properties of gold nanoparticles and silver nanoparticles that are being used in medical treatment so that the problems of conventional materials can be solved. There are also the advantages of organic nanomaterials (e.g., liposomes), i.e., how biocompatibility can play an important role in medical treatment, as well as describing how hybrid nanomaterials can combine and utilize the advantages of different materials. In addition, the paper gives examples of their applications as smart materials, such as precision drug delivery, regenerative medicine and vaccine development, maximizing the possible advantages of their small size, large specific surface area and biocompatibility. Finally, the paper also suggests directions for future improvements of nanomaterials in medicine (e.g., considering their toxicity and biocompatibility in the human body) and possible applications. Even though nanomaterials still have shortcomings, their advantages will certainly advance medical technology, and therefore still require continuous development, exploration and experimentation by researchers.

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