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Nanotechnology is used in molecular biology

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Abstract

Nanotechnology is developing as a new branch of science concentrating on the measurement of tiny materials such as nanometers (between 0.1 and 100 nanometers). Compared to chemical approaches, biogenic synthesis of nanoparticles is affordable and eco-friendly. Overall, this study offers a detailed and unbiased review of the present theories on the uptake of nanoparticles by mammalian cells, considering the complexities of nano-cellular communication. The report also describes the characteristic nature of nanoparticles and their wide spectrum of medical use. In terms of medicine, nanotechnology has brought in some ways of giving new medicines, cancer treatment, and targeted proteins and peptides. This paper is a review of the multifaceted utilities of nanotechnology in the application of drug delivery, diagnosis, and imaging in molecular biology. Furthermore, this review looks into how interactions between nanomaterials and life processes take place and contribute to the ongoing exploration of the nanotechnology-molecular biology conjunction.

Keywords: Nanotechnology; molecular biology; drug delivery; diagnostics; imaging

1. Introduction

Nanotechnology has surfaced as a driving force in molecular biology, as it works with atoms and molecules [1]. First and foremost, what needs to be clarified is the key role nanotechnology plays in molecular biology's confusing territory. The recent integration of nanotechnology and molecular biology is now set for radical developments in the field of healthcare and research [2]. The opportunity to manipulate matter on the nanoscale creates new ways for exact interventions and is a change in paradigm from therapeutic strategies and imaging modalities [3].

Initially, to develop inclusive knowledge on the uses of nanoscale materials, such as in drug delivery systems, diagnostics, and imaging, and later, to explore the complex interactions of nanotechnology and molecular biology and uncover principles that govern nano-cellular phenomena. This investigation is not a survey, but it would be more appropriate to call it a search into the transformative nature of nanotech offerings within the molecular biology realm.

This paper investigates the uses of current nanotechnology findings through their applications in drug delivery, diagnostics, and imaging. It sidesteps the depth of a thorough literature review and premature summarization of findings to open up an analysis of the innovative applications and theoretical basis that comprise nanotechnology and molecular biology.

2. Drug delivery

The use of nanoscale properties is revolutionizing drug delivery. Such nanomaterials involve micelles, liposomes, dendrimers, carbon nanotubes, quantum dots, and metallic nanoparticles [3]. These are elastic carriers of controlled or selective drug release with bioactive supply systems. The comprehensive review by Sim and Wong underscores the importance of quantum dots and nano-detectors, which are much more sensitive and are used in molecular imaging and diagnosis. Moreover, modern nanomaterials have concentrated on increasing their biocompatibility, stability, and controlled release behavior that led to the effective targeting of the delivery system. Researchers are still carrying out studies looking at ways of adding stimulus-responsive components in nanocarriers with the intention of promoting instantaneous as well as maximally effective pharmaceutical consequences.

Successful delivery of therapeutic agents depends on several nano-techniques. Nano-techniques in drug delivery have been categorized into families, with each family having distinctive properties, thus leading to custom-made drug delivery. The first of them is a polymer nanoparticle system [4].

Biological molecules have been concentrated, purified, and confined using polymer nanoparticles. When combined with a complicated biological mixture, polymer nanoparticles can bind specifically to one target molecule, separate it from the medium, and then release the desired molecule [4]. Both in vitro and in vivo biological sensing have been achieved with polymer nanoparticles [5]. Artificial extracellular matrix made of polymer nanoparticles can be effectively used in the culture of different biological tissues [6]. Nonetheless, polymer nanoparticles are mostly employed in the biomedical field as medication delivery systems. When compared to other drug delivery platforms like liposomes or inorganic nanoparticles, polymer nanoparticles provide a number of advantages [4].

The next important nanotechnology for drug delivery is based on inorganic particles. When compared to organic materials, inorganic nanoparticles are hydrophilic, biocompatible, non-toxic, and incredibly stable. They have special optical and magnetic properties, which may be functionalized with different types of specialized ligands to increase their affinity toward molecules or cells of interest [7]. In addition to their capacity to regulate the release profile of pharmaceuticals, inorganic nanoparticles shield pharmaceuticals from deterioration and can lower dosages and frequency of administration, which significantly lowers the toxicity of pharmaceuticals, especially those used to treat cancer. With the development of innovative materials, drug delivery systems with improved drug efficacy and fewer side effects have evolved. Other than calcium phosphates, recent developments in nanotechnology have led to the introduction of other inorganic nanoparticles as effective drug delivery matrices. Nowadays, nanoparticles possess extremely sophisticated chemical characteristics, and numerous inorganic nanoparticles have found application as drug carriers [4]. The use of inorganic nanoparticles for cancer treatment and detection has been the subject of several studies, and the field's applications are constantly expanding.

Viral nanoparticles are used as a mechanism for drug delivery as well. Bacteriophages, together with plant and mammalian viruses, are the sources of a wide range of naturally occurring nanomaterials known as viral nanoparticles (VNPs). The use of virus-like particles (VLPs) and their genome-free counterparts, VNPs, in nanomedicine is expanding quickly [1]. To achieve tissue selectivity, VLPs include a wide variety of active components and are usually chemically or genetically integrated to ligands. The components used to make VLPs are biocompatible and biodegradable, and they are produced by fermentation or molecular farming [8]. Numerous applications, including cancer therapies, immunotherapies, vaccinations, antimicrobial therapy, therapies for cardiovascular diseases, gene therapies, imaging, and theragnostic, have been made possible by these features. In order to bring these treatments to the clinic, enough research must be done consistently on the evolving usage of VLPs as a drug delivery mechanism [9].

In addition, the drug delivery system includes lipid-based nanoparticles. Since the initial clinical approval of Doxil (a drug used in chemotherapy for cancer patients) in 1995, lipid nanoparticles have garnered a great deal of attention and have shown great clinical success over the past 20 years [10]. RNA treatments and mRNA COVID-19 vaccines have been approved, demonstrating the great potential that lipid nanoparticles have shown in delivering nucleic acid medications. One of the best colloidal carriers for organic compounds is lipid-based nanoparticle (LBNP) systems. Their current use in oncology has improved the antitumor mechanism of various chemotherapeutic drugs, revolutionizing the treatment of cancer [11]. Because LBNPs may be made from natural sources, they have several benefits over other materials. These advantages include high loading capacity, low production costs, excellent thermal stability, ease of preparation, and large-scale industrial manufacturing [3]. Furthermore, the combination of lipid nanoparticles and chemotherapeutic drugs lowers the toxicity and active therapeutic dose, lowers drug resistance, and raises drug levels in tumor tissue by lowering levels in healthy tissue. LBNPs have been thoroughly investigated for both in vivo and in vitro cancer therapy, with encouraging outcomes in a few clinical trials [12].

An additional useful drug delivery system is nab-technology (nanoparticle albumin-bound). By mixing two immiscible substances-albumin, an aqueous protein, and a solvent-based agent-nanoparticle albumin-bound (Nab) drug delivery is utilized to give chemotherapy treatment with fewer adverse effects than traditional approaches. Achieving a uniformly tiny size of the particle is a crucial first step towards developing this extremely essential targeted medication delivery technique. When it comes to delivering high-toxicity, low-aqueous solubility therapeutic drugs with fewer adverse effects than conventional methods, nanoparticle albumin-bound (nab) technology is a valuable carrier that is best suited for usage in chemotherapy treatment [2]. The first nab drug delivery system formulation authorized by the FDA is paclitaxel, which is a nanoparticle albumin-bound formulation. Nab-paclitaxel, a potent chemotherapeutic agent, is marketed under the trade name Abraxane® and is utilized to treat non-small lung malignancies, metastatic breast cancers, and advanced pancreatic cancers. Using HSA (human serum albumin) as a drug delivery carrier can greatly minimize the severe side effects and high toxicity of the active chemical, solvent-based paclitaxel, which patients experience [13].

According to research by Xu et al., surface functionalization, stimuli-responsive drug carriers, and active targeting strategies improve delivery accuracy and effectiveness. In addition, the use of advanced artificial intelligence in some nano-techniques has demonstrated some encouraging predictions towards individualized treatments [10].

3. Diagnostics

With respect to nanomaterials, it enhances diagnostic capabilities. Classified for their diagnostic applications are gold nanoparticles, silver nanoparticles, silica nanoparticles, carbon nanotubes, and quantum dots [14]. A current study by Thwala et al. is about nano-diagnostics and diseases found mostly in developing countries. The study underscores the revolutionary role of nanomaterials in point-of-care testing (POCT) for both infectious and non-infectious diseases. In addition, current studies are also looking into blending nano-diagnostics with artificial intelligence algorithms for increased sensitivity and specificity in the test results for better disease diagnosis in different hospital setups. As the development of nano-diagnostics improves, attempts are being made to make these technologies more available and affordable, especially in developing countries. Diagnostic nanotechnologies include microfluidics, lab-on-chip (LOC), and lateral flow immunoassay chips [14].

A tiny, highly ordered, non-turbulent, fluid system that consists of various microchannels etched into a material called a microfluidic system [15]. These microchannels can be designed to carry out complicated tasks, much like electrical circuits. Their size is typically a few hundred micrometers, and they are used in carefully monitored biological research. The microfluidic chips' microchannels are linked together to provide a variety of intended functions. For instance, the system's ability to carry out sample separation, mixing, dilution, chemical reaction, and product extraction can be achieved by connecting the channels [14]. Lab-on-chip (LOC) devices are microfluidic devices that combine one or more of these laboratory operations onto an integrated circuit. Microfluidic systems can be considered a potential replacement for the macroscale systems seen in a normal bioscience or biomedical lab because of their wide variety of applications. The unique properties of microfluidic diagnostic chips, such as their mobility, minimal reagent and sample intake, high sensitivity, and modularity, make them appropriate for point-of-care applications (POCT) [16]. In situations where extremely low amounts of samples are accessible on demand and where resources are limited, such as disease diagnosis at the point of care (POC), reduced reagent use in microfluidics is advantageous [16]. Disease detection devices that can be incorporated at or close to POC, or the location and time of patient care, are known as point of care (POC) diagnostic testing devices [17]. To become more similar to POC devices, microfluidic chips can be coupled with various biosensing setups or used as independent biosensing devices [18]. These biosensors may be colorimetric, magnetic, electrical, optical, electrical, or electrochemical biosensors [14]. Depending on the application, they can have a wide variety of microchannel types, such as microstructured surfaces, droplet generation, laminar flow, hydrodynamic focusing, serpentine, spiral, gated parallel, mixing, and microchip channels [19]. Microstructured surfaces are also possible. Microfluidic chips are very versatile, dynamic, and adaptive devices for biosensing applications because of all these characteristics [14].

By merging quantum dots and microfluidics, Klostranec et al. created a diagnostic device that is a potent tool for multiplexed, high-throughput analysis of infectious pathogens in human serum samples. This technique has proven to be incredibly sensitive and quick at detecting serum biomarkers of common bloodborne viral illnesses like HIV, hepatitis B, and hepatitis C [20]. The system needs less than 100 µL of serum to function, and it is made to work with minimal sample volumes. Because of this capability, it's a useful tool in clinical contexts where sample sizes might be restricted. Furthermore, the system's speed makes it possible to analyze big sample sets effectively, which makes it a desirable choice for screening. Low concentrations of infectious agents can be found using this characteristic, which may not be possible with conventional techniques. Quantum dots, which are extremely fluorescent nanoparticles that provide light signals when attached to target proteins, are used to achieve the high sensitivity [20]. With further development, this novel tool could become a useful point-of-care (POC) diagnostic instrument, which would be a major breakthrough in the identification, tracking, management, and containment of the spread of infectious diseases in underdeveloped nations. Because of its affordability, simplicity of use, and accessibility, the lateral flow immunoassay (LFIA) is the most often used method for quick diagnostic testing. Nitrocellulose membrane, adsorbent pad, conjugate pad, sample application pad, and LFIA strip are its constituent parts [14]. The biomolecule conjugate is released from the conjugation pad and passes through the nitrocellulose membrane when a sample is applied to the sample application pad [21]. There, it binds to the primary biomolecule in opposition to the analyte at the test line. The secondary biomolecule in the control line attaches to the released biorecognition molecule and causes a color to emerge, signaling that the test is functioning properly. This method has been applied extensively to provide a quick response in serological testing for rapid diagnosis [21]. With the goal of enhancing decision-making and turnaround time, LFIA, along with other point-of-need diagnostics, has symbolized a paradigm change from sample-to-lab to lab-to-sample [14]. Because of its advantages, LFIAs are a very appealing tool for clinical diagnostics, where their ability to facilitate quicker diagnosis decisions and treatment can enhance patient care. The widespread adoption of LFIAs can be attributed to their speed, ease of use, affordability, and suitability for non-expert staff.

To improve the precision and efficiency of diagnostics, significant efforts have been undertaken to incorporate nanotechnology, materials science, microfluidics, and microelectrochemical systems. Consequently, miniaturized, automated, and incorporated technologies have emerged as preferred alternatives to conventional techniques for quick, affordable, precise, on-site (POC) diagnosis [14]. Numerous microfluidic systems that combine many techniques have surfaced, including lab-on-chip (LOC) devices.

POCT has transformed medical testing, especially with limited resources. Nanotech has helped create simple, low-cost diagnostics that can even be conducted in rural areas. Moreover, nanodevices coupled with smartphone apps are making it possible for decentralized diagnostics, allowing the real-time tracking of the health status.

4. Imaging

Nanoparticles, nanorods, nanospheres, nano-shells, and nano-stars are vital in the imaging world [22]. These materials have many functions in biomedical imaging and cancer therapy, where they function as drug carriers, imaging contrast agents, photothermal agents, photoacoustic agents, and radiation dose enhancers. They show flexibility as well as multidimensional roles that nanoparticles can assume in the medical imaging field. Additionally, recent investigations have concentrated on the possibility of creating nano-functional materials that have the ability to image and treat simultaneously to cover the aspect of diagnosis and therapy.

Magnetic Resonance Imaging (MRI), Positron emission tomography (PET), Computed Tomography (CT), fluorescence, and optical imaging use several non-techniques. By using biliverdin nanoprecipitation, an imaging probe that is digested metabolically was created. These NPs are made up of a network of biliverdin and have an amine linker cross-linking them. Their powerful photoacoustic signal is produced by stimulation at Near-infrared (NIR wavelengths [23]. The nanocomplex is composed of switchable Raman reporters to facilitate the assembly of gold NPs into photonic clusters and a fluorescent protein fragment that serves as a molecular glue. An improved Photoacoustic signal (PA) is produced by the fluorescent protein-driven synthesis of metal colloids, which can be utilized as a PAI (Photoacoustic imaging) agent [24]. Clofazimine hydrochloride NPs, an FDA-approved antimycobacterial medication, were combined to create a photoacoustic contrast agent that was intended to be utilized for prostate cancer. It was able to target macrophages and exhibited a strong absorbance contrast at 495 nm. A preferential buildup of NPs in a malignant prostate cell over the control sample was demonstrated by the experimental results in the mouse prostate model on transgenic adenocarcinoma. This makes prostate cancer analysis and PAI possible [25]. Photoacoustic imaging can produce useful endogenous contrast from melanin and oxy-/deoxyhemoglobin, and it can penetrate a few centimeters. ICG is a molecule dye that can be used for PAI. It has quick clearing, bleaching effects, and quick protein binding [22].

An X-ray source and an array detector are used in computed tomography to create images. It can generate an image with great spatial and temporal resolution, which is why it has been used extensively in clinical imaging for a long period of time. It can deliver 3D information of particular tissues and organs, including the liver, lung, gastrointestinal tract, and cardiovascular system [22]. One limitation of CT is that, in contrast to other modalities like MRI, it is not as sensitive to contrast chemicals. Still, there aren't many effective contrast agents for CT accessible [26]. One method of imaging used in nuclear medicine is positron emission tomography, or PET. It creates photographs of the spread of radio-nuclides using radiotracers. Through a noninvasive technique, these tracers can offer information on cellular pathways [27]. In PET, gold nanoparticles are frequently utilized. Recently, highly sensitive, stable, and biocompatible imaging agents have been developed, making it possible to visualize dendritic cell movement [28]. Monitoring the migration of dendritic cells is crucial for immunotherapy based on dendritic cells. Different kinds of autophagy-related structures can be seen at both the macroscopic and microscopic levels using noninvasive optical imaging. Fluorescence, chemiluminescence, and Raman imaging are examples of optical imaging techniques that can provide noninvasive two- or three-dimensional picture data at the macro and micro scales. Compared to other techniques, fluorescence imaging yields data that are easier to understand, requires less time, and is an intuitive method. For this reason, it is frequently chosen by researchers and applied in biological imaging [21].

In the study published in 2020 on NCBI, researchers Siddique and Chow examined how nanoparticles have changed imaging and highlighted current advances in multimodality imaging, image-guided therapy, and combination therapy. This review underlines the potential benefits of these technologies for medical imaging and cancer therapy, but it also calls for more research on cell toxicity in humans. In addition, research is geared towards real-time imaging with nano sensors that facilitate dynamic monitoring of physiology and treatment response in vivo. Additionally, the use of artificial intelligence algorithms in image analysis makes these real-time imaging approaches more accurate and increases their diagnostic abilities [22].

5. Theory/calculation of the study

Expanding on the basics set out in the introduction, the theory section broadens the conceptual framework of nanobiotechnology. Essentially, nanotechnology is based on quantum mechanics and the ability to handle matter in nanometers. For instance, quantum dot theory guides the manufacture of these nano-sensors and creates a sound theoretical basis for their unusual optical properties that are used in fluorescence imaging [29]. Molecular dynamics simulations play the role of “a virtual lab”, which enables us to understand possible interactions at the molecular level between nanomaterials and biological substances. The latter is a theoretical approach that guides the rational design of drug delivery carriers and helps anticipate their behavior in biological systems. However, tailor-made designs of nanomaterials taking into consideration material science principles of surfactancy and thermodynamics aim to improve biocompatibility and cellular uptake [30].

In particular, the calculation section is more than just a mere translation of these theoretical foundations into real projects. For instance, quantum dot theory manifests itself through synthesizing quantum dots possessing the desirable optical parameters that can be utilized for fluorescence imaging. The design of drug delivery carriers involves molecular dynamics simulations that provide directions for creating systems with satisfactory pharmacokinetic profiles [31].

Their application in practice is facilitated by the theoretical interpretation of various mechanisms of cellular uptake that help predict nanocarrier penetration through biological barriers [30]. The practical use of controlled-release systems is based on predictive models for drug release kinetics from nanoparticles. During their research, Aliakbarinodehi et al. discussed how this synergy of theory and practice facilitates innovation because the knowledge derived theoretically contributes to more practical strides in nanotechnologies in molecular biology. The theory/calculation part ties the theoretical basis of nanotechnology to its practical applications. This integrative approach provides a direction from conceptual ideas to practical application in drug delivery, diagnostics, and imaging [32].

6. Drug delivery methods

In **Error! Reference source not found.**, We show the encapsulation of therapeutic agents into polymeric nanoparticles and a controllable release profile. The sustained release kinetics could potentially provide therapeutic effects over a long period of time. Further, the coating of targeting ligands showed that there is an improved level of cellular uptake, as seen in **Error! Reference source not found.**. As shown by Bajracharya et al. in Figure 3a ligand-modified nanocarrier demonstrates active tumor-targeting through engagement with overexpressed antigens and receptors inside a tumor. These include functional ligands such as folic acid, hyaluronic acid, transferrin, peptides, and antibodies. The implications for precision medicine by nanocarriers. Furthermore Table 1 demonstrates ligands for active targeting nanoparticle drug delivery systems.

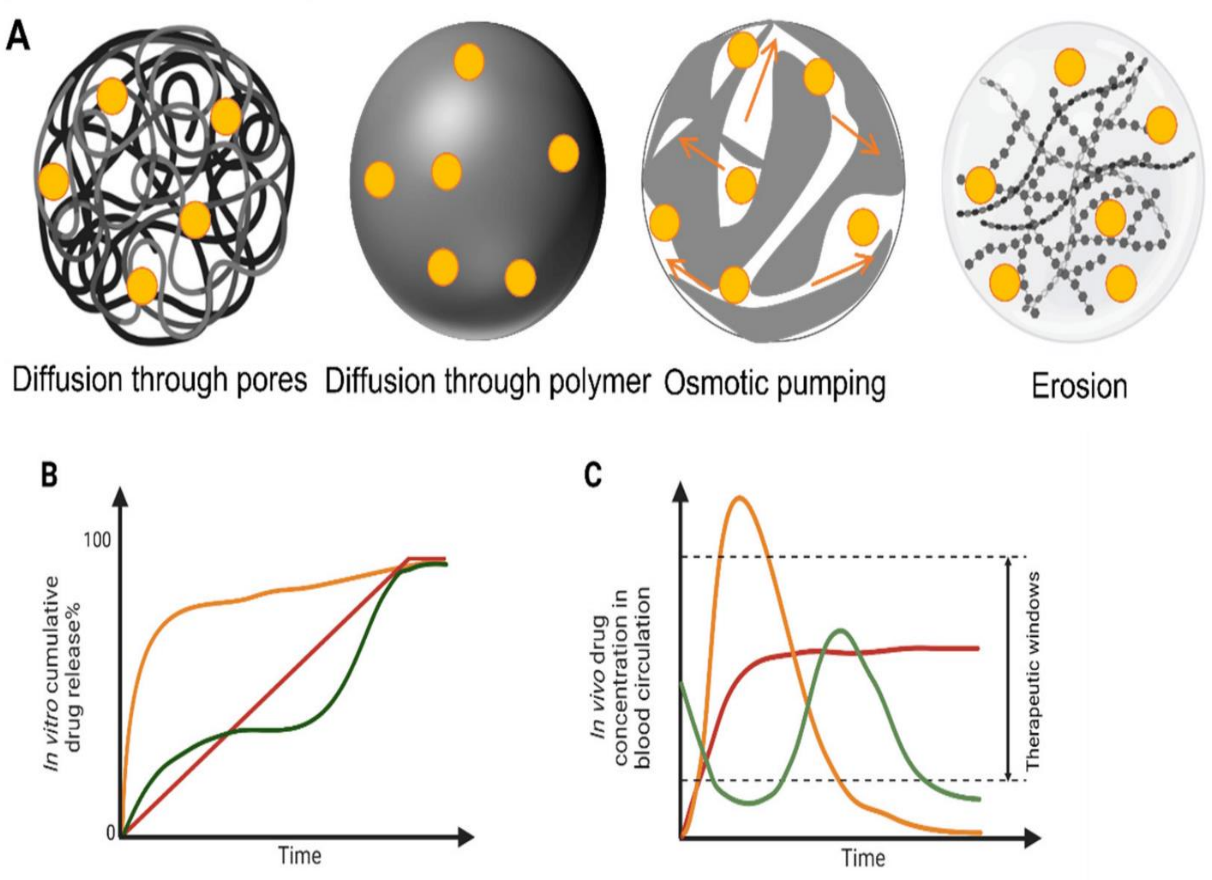

Figure 1. Sustained Release Kinetics of Therapeutic Agents from Polymeric Nanoparticles [23]

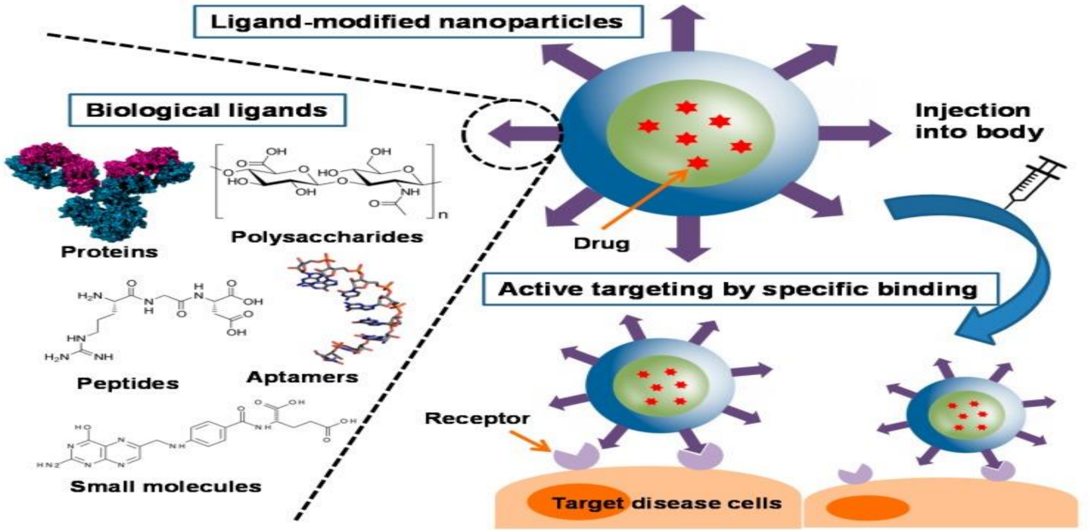

Figure 2. Illustration of biological ligands for active targeting of nanoparticle drug carriers [23]

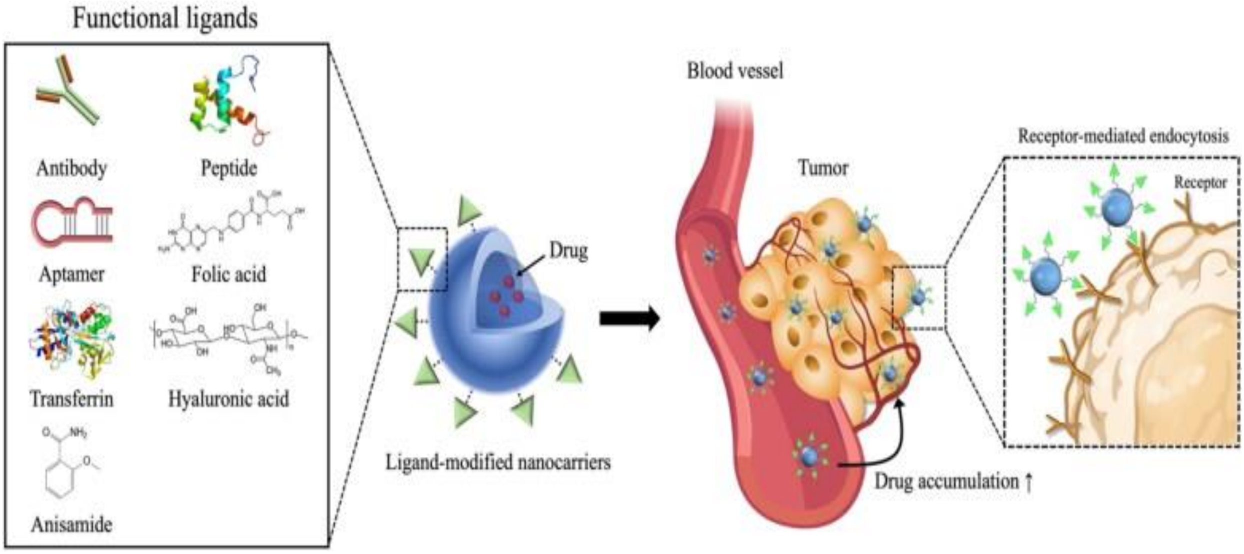

Figure 3. Ligand-modified nanocarriers offer active tumor-targeting by interacting with overexpressed antigens or receptors in tumors. Functional ligands like folic acid, hyaluronic acid, transferrin, peptides, and antibodies are explored [23]

Table 1. Ligands for active targeting of nanoparticle drug delivery systems

Type	Ligands (Example)	Advantage/Disadvantage
Proteins	Antibodies, transferrin	large specificity/large size, low stability
Polysaccharides	Hyaluronic acid	Can be used as a polymer backbone of nanoparticles/overexpressed receptors in liver tissue
Peptides	RGD, IL4RPep-1	Easy fabrication, small size/cleavable by peptidase
Aptamers	AS-1411, GBI-10	High specificity, small size/cleavable by nuclease, high cost
Small molecules	Folate, anisamide phenylboronic acid	Small size, very low cost/target are also expressed in normal tissues

7. Diagnostics

Nanomaterials have been exploited in the development of highly sensitive biosensors in the diagnostics arena. This is demonstrated by the curve in

Figure *4*, which indicates a biomolecule sensor capable of low concentration detection. During their research, Aliakbarinodehi et al. discussed that development has significant implications for the early diagnosis and surveillance of disease [32].

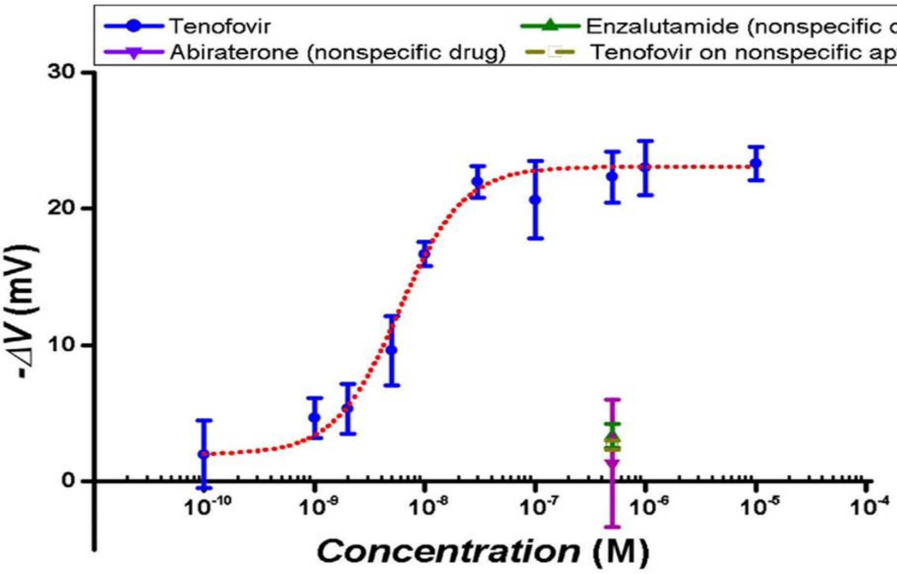

Figure 4. Dose-Response Curve of Biosensor for Biomolecule Detection

In Figure 5 the demonstration of the potential of quantum dots as a means of real-time visualization at the molecular scale for fluorescence imaging is shown.

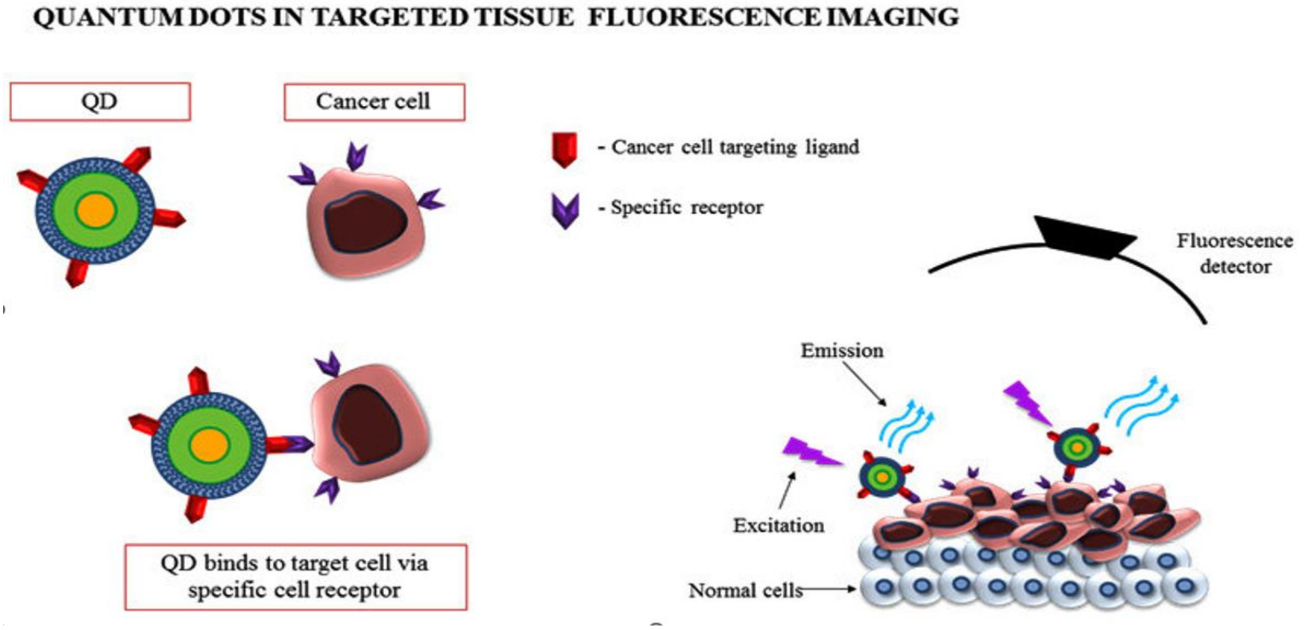

Figure 5. Quantum Dots in Targeted Tissue Fluorescence Imaging [23]

8. Imaging techniques

As previously stated, magnetic nanoparticles can be used as contrast agents in MRI. In Figure 6we present the contrast of imaging improvement. The outcomes are precedent to the possible role of nanotechnology in medical imaging with improved diagnostic accuracy [31].

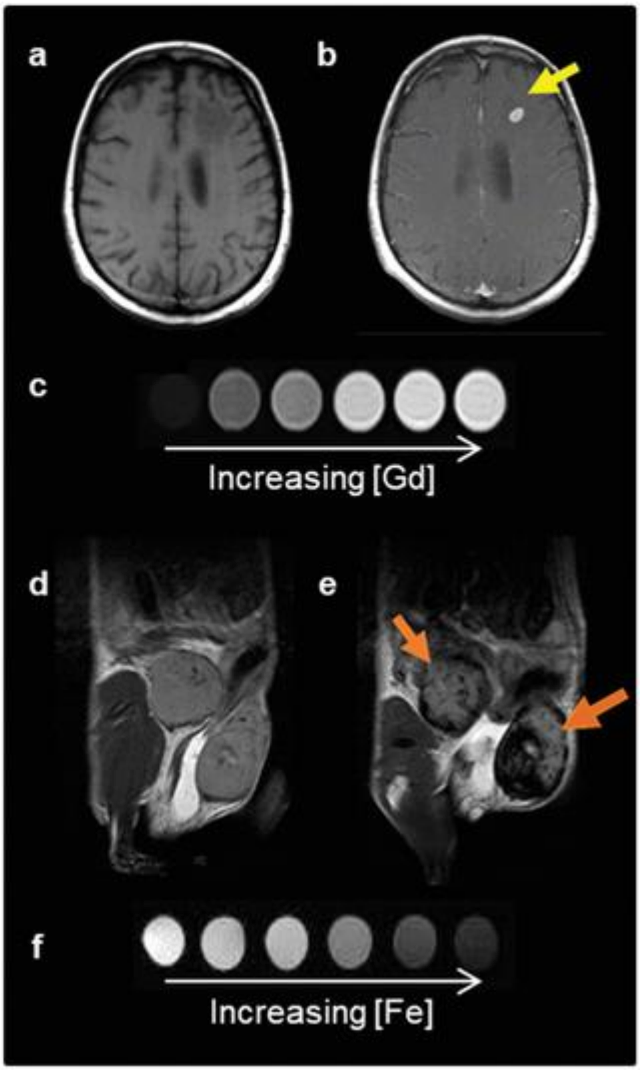

Figure 6. Enhanced Imaging Contrast with Magnetic Nanoparticle Contrast Agents in MRI [21]

The obtained results collectively confirm the potential of nano-scale materials for further advancement in diagnostics, imaging, and drug delivery in molecular biology. The resulting figures and tables complement clarity and exhibit our findings [31].

9. Discussion and conclusions

These findings demonstrate the dawn of a new era in molecular biology through nanotechnology, with implications for drug delivery, diagnostics, and imaging. Sustained release or targeted therapeutic agents offer potential for enhancing patient compliance and treatment effectiveness. Targeting ligands is further beneficial in cell-specific delivery of nanoparticles to reduce off-target effects, which is an important aspect of personalized medicine. As discussed by Jeon et al, highly sensitive biosensors promise more exact molecular diagnostics. Early disease detection and intervention at early, treatable stages, in particular, the application of

quantum dots to fluorescence imaging as demonstrated in this paper, not only facilitates real-time visualization but also implies the prospect for intraoperative sensing and even tracking of cellular processes.
This is a breakthrough in medical imaging, where magnetic nanoparticles were successfully used as contrast agents in MRI.

In conclusion, this study explores the use of nanoscale materials and methods in molecular biology through drug delivery, diagnostics, and imaging. The findings highlight the emergence of nanotechnology as a new frontier in healthcare and research. The polymers would become a major breakthrough in therapeutics, as evidenced by the success that polymeric nanoparticles have shown up until now in achieving controlled, sustained drug release. The use of magnetic nanoparticles as contrast agents in MRI is a new paradigm in medical imaging that improves anatomical visibility and produces strong contrast. These collective developments are not only shaping nanotechnologies in relation to molecular biology but are also reflecting a wider trend toward personalized and precision medicines. Viewed separately or as an essential component of the overall narrative, this review only further highlights the importance that nanotechnology plays in the mysterious world of molecular biology.

Declaration of Competing Interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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