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Original Article

Application of nanomedicine in cancer diagnosis and therapy

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ABSTRACT

Nanotechnology is a field of study that involves uses of materials in nano form (1-100nm). Out of many branches of nanotechnology, nanomedicine is a branch that is related to pharmaceutical and health sciences. In nanomedicine, nanomaterials and nanoparticles are being used in the diagnosis of various diseases and deliverance of various pharmaceutical and nutraceutical products to the body system. Application of nanoparticles in drug delivery has conferred many advantages to the efficacy and utilization of the drugs. Some of those advantages conferred by the nano-carried drugs over those administered in conventional forms include increase in therapeutic index, biocompatibility, biodegradability, bioavailability and reduction in toxicity. Cancer diagnosis and drug delivery nanoparticles include and not limited to metallic nanoparticles, polymers nanoparticles, carbon nanoparticles, nanotubes, liposomes-based nanoparticles, dendrimers, quantum dots, ceramic nanoparticles, nano-erythrosomes and various nanocomposites. Out of these nanoparticles, serious detrimental health concerns are expressed on the uses of metallic nanoparticles and their composites because of their pro-oxidant properties which contribute to their toxicities. Nevertheless, polymer nanoparticles such as chitosan nanoparticles and membrane-based nanoparticles are reported to exhibit high biocompatibility and biodegradability with less toxicity over metallic nanoparticles. However, the expensiveness, inaccessibility and fear of toxicity of some of these nanocarriers constitute the limiting factors surrounding the uses of nanomaterials for drug delivery system meant for cancer therapy.

Keywords: Cancer, Diagnosis, Therapy, Nanomedicine, Nanotechnology.

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INTRODUCTION

Nanomedicine has emerged as a promising approach in cancer management. It involves the biomedical application of materials with at least one dimension below 100 nm, although structures up to 200 nm are often included in practice (1). Conventional chemotherapeutic agents are frequently limited by poor therapeutic efficacy and severe adverse effects. Nanomedicines can improve drug biodistribution and tumor accumulation, thereby enhancing therapeutic outcomes while reducing systemic toxicity (2). Advances in Nano medicine have also contributed to the development of personalized medicine. Effective cancer treatment requires the selective delivery of therapeutic agents to tumor tissues, and extensive efforts over the past two decades have focused on designing nanomaterial-based drug delivery systems for site-specific therapy. In addition, theranostic platforms combine diagnostic and therapeutic functions within a single system, enabling disease monitoring alongside
targeted drug delivery (3).

Nanomedicines encompass a wide range of platforms, including liposomes, nanoparticles, micelles, dendrimers, and nanotubes, which may be composed of lipids, polymers, proteins, inorganic materials, or their combinations. Some nanomedicine-based products, such as Doxil and Abraxane, have achieved clinical success in breast cancer treatment. With increasing knowledge of breast cancer biology, more specialized nanodelivery strategies are being developed to improve therapeutic precision. Beyond drug delivery, nanomedicine also supports cancer diagnosis, imaging, tissue repair, and theranostic applications (1). Therefore, this review highlights the current applications and emerging trends of nanomedicine in cancer diagnosis and therapy.

Nanoparticles Used in Cancer Treatment

There are different types of nanoparticles, but not all are used in cancer treatment. Below are few nanoparticles which are used in cancer treatment.

Organic Nanoparticles

Chitosan-Based Nanoparticles for Cancer Therapy

Chitosan and its derivatives have been widely investigated as carriers for anticancer drug delivery because of their biocompatibility and versatility. Chitosan ascorbate nanoparticles have shown selective cytotoxicity against cervical cancer cells while exhibiting minimal effects on normal cells, highlighting their potential for targeted therapy (4).

Surface modification further enhances the therapeutic performance of chitosan nanoparticles. EGFR-targeted chitosan nanoparticles effectively delivered Mad2 siRNA to non-small cell lung cancer cells, resulting in gene silencing, apoptosis, and significant tumor inhibition in both cisplatin-sensitive and resistant models. Similarly, folate-modified chitosan nanoparticles improved the delivery and anticancer activity of curcumin in breast cancer cells while maintaining low toxicity toward normal cells (5).

Chitosan-based multifunctional nanoparticles have also been developed for doxorubicin delivery. These systems enhanced tumor targeting, promoted pH-responsive drug release, and achieved superior tumor suppression with reduced systemic toxicity compared with free drug treatment (6).

Dextran-Based Nanoparticles for Cancer Therapy

Dextran has attracted considerable interest as a nanocarrier for anticancer drug delivery due to its ability to self-assemble with therapeutic agents. Curcumin, a polyphenolic compound with anticancer properties, has been conjugated to dextran to form self-assembled nanoparticles for drug delivery applications. Curcio *et al*., (7) developed dextran-curcumin nanoparticles for the delivery of methotrexate in breast cancer therapy. The nanoparticles enabled sustained drug release and rapid cellular uptake by MCF-7 cells. Furthermore, methotrexate and curcumin exhibited synergistic anticancer activity, highlighting the potential of drug-polymer conjugates in combination therapy (7).

Dextran nanoparticles have also been explored for photodynamic therapy. Lee *et al*. (8) developed chlorin e6-loaded dextran nanoparticles coated with gold nanoparticles to improve stability. The formulation remained stable in serum and demonstrated efficient uptake by SCC7 cells. In vivo studies showed enhanced tumor accumulation of chlorin e6 and superior antitumor activity compared with free chlorin e6 or uncoated dextran nanoparticles, owing to improved protection and delivery of the photosensitizer to tumor sites.

Targeted dextran-based systems have also been designed to improve chemotherapeutic efficacy. Tang *et al*. (9) developed folic acid-conjugated dextran nanoparticles for doxorubicin delivery. In addition to promoting drug loading, folic acid facilitated targeting of folate receptor-overexpressing cancer cells. The nanoparticle formulation produced greater tumor inhibition and prolonged survival in 4T1 tumor-bearing mice compared with free doxorubicin and non-targeted formulations, demonstrating the potential of dextran-based nanoparticles for targeted cancer therapy.

Albumin-Based Nanoparticles for Cancer Therapy

Albumin is one of the most widely used natural nanocarriers for cancer drug delivery due to its biocompatibility, biodegradability, and ability to improve the solubility and bioavailability of therapeutic agents. Both bovine serum albumin (BSA) and human serum albumin (HSA) have been extensively investigated for the delivery of anticancer drugs and natural compounds.

The BSA nanoparticles have been shown to enhance the therapeutic efficacy of bioactive compounds such as piceatannol, curcumin, and doxorubicin. For example, piceatannol-loaded BSA nanoparticles exhibited improved anticancer activity against colon cancer cells and greater tumor suppression in animal models compared with the free drug (10). Similarly, co-encapsulation of curcumin and doxorubicin in albumin nanoparticles helped overcome adaptive treatment tolerance and improve drug retention in resistant breast cancer cells (11). Albumin-based systems have also been employed for the co-delivery of doxorubicin and cyclopamine, resulting in reduced drug resistance, enhanced tumor targeting, and inhibition of metastasis in breast cancer models (12).

The HSA nanoparticles have likewise demonstrated significant potential in overcoming multidrug resistance and improving therapeutic outcomes. Encapsulation of doxorubicin in HSA nanoparticles enhanced cytotoxicity in resistant neuroblastoma cell lines and restored drug sensitivity in resistant cells (13). Other studies have shown that doxorubicin-loaded HSA nanoparticles

suppress tumor growth and metastasis while reducing systemic toxicity compared with the free drug (14; 15).

Gelatin-Based Nanoparticles for Cancer Therapy

Gelatin-based nanoparticles have been widely investigated as drug delivery systems for various cancers due to their biocompatibility, biodegradability, and responsiveness to the tumor microenvironment. Raza *et al*. (16) developed paclitaxel-loaded gelatin nanoparticles for intravesical bladder cancer therapy. The formulation protected paclitaxel from dilution by urine, enabling sustained drug retention in bladder tissues and maintaining therapeutic concentrations for up to one week.

To improve tumor targeting, Zhang *et al*. (17) functionalized gelatin nanoparticles with 3-carboxyphenylboronic acid (3-CPBA), which targets sialic acid overexpressed on tumor cells. The modified nanoparticles exhibited enhanced cellular uptake, greater tumor accumulation, and superior antitumor activity compared with free doxorubicin and unmodified nanoparticles. Similarly, matrix metalloproteinase-2 (MMP-2)-responsive gelatin nanoparticles have been developed to improve intratumoral drug penetration. Zhang *et al*. (17) demonstrated that gelatin degradation within the tumor microenvironment facilitated deeper penetration of doxorubicin, while Xu *et al*. (18) reported MMP-2-responsive nanoparticles co-delivering doxorubicin and 5-aminolevulinic acid, producing synergistic chemo-photodynamic effects with reduced cardiotoxicity.

Gelatin nanoparticles have also shown promise in lung cancer therapy. Resveratrol-loaded gelatin nanoparticles exhibited sustained drug release, enhanced cellular uptake, and improved antitumor activity in non-small cell lung cancer (NSCLC) models compared with free resveratrol (19). Targeted delivery approaches have further been explored using phytohemagglutinin erythroagglutinating (PHA-E)-modified nanoparticles for gemcitabine delivery, resulting in EGFR-mediated inhibition of NSCLC cell growth and induction of apoptosis (20). In pancreatic cancer, EGFR-targeted thiolated gelatin nanoparticles have been employed for the delivery of gemcitabine and wild-type p53 plasmid. Both formulations demonstrated significant antitumor activity, while combination treatment produced superior therapeutic outcomes compared with either agent alone (21).

Liposomes

Liposomes are phospholipid-based vesicles widely used for the delivery of anticancer agents due to their biocompatibility, ability to encapsulate diverse drugs, and structural similarity to biological membranes. Conventional, PEGylated, and surface-modified liposomes have been extensively investigated to enhance drug delivery and therapeutic efficacy in cancer treatment (22).

Recent developments have focused on biomimetic and hybrid liposomal systems. Cell membrane-coated liposomes, including macrophage- and erythrocyte-derived formulations, have demonstrated enhanced tumor targeting, sustained drug release, and improved therapeutic outcomes in cancer models (23). Hybrid liposomes incorporating natural polymers or inorganic nanomaterials have also been developed to improve stability, bioavailability, and tumor accumulation. Examples include chitosan-liposome systems for curcumin delivery and

liposome-coated gold nanoparticles for targeted cancer therapy (24).

Cell Membrane-Based Drug Delivery Systems

Cell-based drug delivery systems, including whole cells, extracellular vesicles (EVs), and cell-derived membranes, have gained considerable attention in cancer therapy. Because these systems are derived from endogenous sources, they exhibit low immunogenicity and toxicity. Unlike conventional lipid-based carriers, cell membranes possess complex biological components such as proteins, carbohydrates, and antigens that contribute to functions including cellular communication, immune evasion, and tissue-specific targeting. These biological characteristics are largely preserved during formulation, enabling the transfer of native cellular functions to the drug delivery system (25).

Among cell-based platforms, cell-derived membranes offer the greatest flexibility for engineering biomimetic nanocarriers. They are commonly used to coat nanoparticles, including polymeric, gold, and silica nanoparticles, forming core-shell structures that combine the biological advantages of cell membranes with the physicochemical properties of synthetic nanomaterials. Such biomimetic systems have shown significant potential for targeted and efficient cancer drug delivery (25).

Cyclodextrin Inclusion Complex

Cyclodextrins (CDs) are natural cyclic oligosaccharides that have a cavity for encapsulating various molecules to improve their solubility, bioavailability, stability and permeability. Furthermore, CDs can be grafted onto other natural ingredient-based DDSs such as nanoparticles or hydrogel for functionalization of the system (26).

Inorganic Nanoparticles

Metallic nanoparticle

Metallic Nanoparticles (MNPs) have a diversity of biomedical usages, including their use in sensitive detection, drug delivery, genetic material, thermal abrasion, and radiation therapy enhancement. MNPs have better Permeability and less toxicity than non-infected cells compared to conventional forms. The important role of MNPs in the clinical context of cancer treatment is extensive optical properties, high surface-to-volume ratio, easy synthesis and chemistry, and facial surface function (27). MNPs and metal oxide NPs (MONPs) have effective anticancer activity in various types of cancer, such as breast cancer, lung, colorectal, pancreatic, and skin cancers. Different MNPs and MONPs have a better cytotoxic efficacy on skin cancer than conventional dosage forms (28). Other MNPs and MONPs applications include detecting and imaging cancer cells, making them promise for treating and assessing skin cancer. Below are examples of metallic nanoparticles used in cancer treatment.

Gold Nanoparticles

Gold nanoparticles (AuNPs) are widely investigated inorganic nanocarriers for cancer therapy due to their tunable size, shape, and surface characteristics. Their unique surface plasmon resonance (SPR) properties make them valuable for cancer imaging, biosensing, photothermal therapy, and targeted drug delivery (29). In addition, their large surface area enables efficient conjugation of drugs, nucleic acids, proteins, and targeting ligands, while their stability and

biocompatibility support biomedical applications (30).

The AuNPs have emerged as promising non-viral gene delivery vectors because they protect nucleic acids from degradation and exhibit lower immunogenicity than viral systems. They have been successfully used to deliver antisense oligonucleotides for gene silencing in breast cancer cells (31). Furthermore, their photothermal properties enable combination therapies involving gene therapy, chemotherapy, and photothermal treatment, leading to enhanced antitumor efficacy with minimal toxicity (32).

Iron Nanoparticles (FeNPs)

Iron nanoparticles (FeNPs), particularly iron oxide nanoparticles, are widely explored for cancer diagnosis, therapy, and theranostics because of their unique magnetic properties (33). Their superparamagnetic behavior has enabled applications in magnetic resonance imaging (MRI), magnetic particle imaging (MPI), magnetic drug targeting, and magnetic hyperthermia. The FeNPs also serve as promising drug and gene delivery platforms. Doxorubicin-loaded FeNPs have been investigated for glioblastoma treatment, while magnetic nanoparticles have been utilized for siRNA delivery as a safer alternative to viral vectors (33). Surface modification with polymers or targeting ligands further improves their stability, biocompatibility, and tumor-targeting ability, as demonstrated by LHRH-conjugated iron oxide nanoparticles for breast cancer imaging and therapy (34).

In addition, FeNPs have shown considerable promise in magnetic hyperthermia and several formulations, including Feridex® and Resovist®, have reached clinical application or evaluation. However, challenges such as limited tumor distribution and dependence on external magnetic fields continue to hinder their broader clinical translation (35).

Silica Nanoparticles

Silica being a significant component of many natural materials, was only studied concerning biology recently. Silica NPs are commonly used to deliver genes by functionalizing the NP surface with amino-silicanes (36). N-(6-aminohexyl)-3-aminopropyl-trimethoxysilane functionalized silica NPs have shown excellent efficiency in the transfection of Cos-1 cells with minimal toxicity and is now commercially available (37). Mesoporous silica NPs are considered one of the best drug carriers due to their better pharmacokinetic properties. They have been extensively used in immunotherapy. According to a study, colorectal cancer cells have shown successful uptake of camptothecin-loaded mesoporous silica NPs.

Carbon Nanoparticles

Carbon NPs as the name suggests are based on the element carbon. They have been widely utilized in medical arenas because of their optical, mechanical, and electronic properties combined with biocompatibility (38). Due to their inherent hydrophobic nature, carbon NPs can encapsulate drugs through π-π stacking (39). Carbon NPs are further categorized into graphene, carbon nanotubes, fullerenes, carbon nanohorns, and graphyne. Although all these are carbon-based, they vary in their structure, morphology, and properties.

Graphene

Graphene is a 2D crystal with SP^2-hybridized carbon sheet that holds extraordinary mechanical,

electrochemical, and high drug loading properties. Further, based on composition, properties, and composition, graphene can be divided as follows: 1) single-layer graphene, 2) grapheme oxide (GO), 3) reduced graphene oxide (rGO), and 4) multi-layer graphene (40). GO and rGOs are widely used due to their ability to target hypoxia and irregular angiogenesis in TME. Studies have shown that GO-doxorubicin exhibits higher anticancer activities in cellular models of breast cancer (41).

Fullerenes

These are large carbon-cage molecules composed of carbon allotrope with different conformation types such as sphere, ellipsoid, or tube. They are the most widely studied nanocarriers as they have typical structural, physical, chemical, and electrical properties (42). These are used in photodynamic therapy as they have triple yield and generate oxygen species due to the presence of extended π-conjugation and the ability to absorb light. PEG-modified fullerenes showed promising photodynamic effects on tumor cells (43).

Carbon nanotubes (CNTs)

These are cylindrical tubes, most often considered as rolls of graphene, and were discovered in the late 1980s. They are classified into two groups: 1) single-walled CNTs and 2) multi-walled CNTs. As they are carbon-based, they can bring upon immune response by interacting with immune cells, thereby suppressing the tumor growth. Traditionally, they have been used as DNA delivery vectors and for thermal ablation therapy. For instance, a fluorescent single-walled CNT with mAb encapsulating doxorubicin is used to target colon cancer cells. Such CNTs form a complex which is effectively engulfed by the cancer cells leading to the intracellular release of doxorubicin, whereas the CNTs are retained in the cytoplasm (44).

Quantum Dots

Quantum dots are typically nanometer-scale semiconductors with a broad spectrum of absorption, narrow emission bands, and high photostability, allowing them to be widely used in biological imaging (44). The most commonly used quantum dots are graphene quantum dots due to their inherent biocompatibility and rapid excretion. For example, quantum dots aptamer-doxorubicin conjugate targets prostate cancer cells (45). However, the deficiency of optimized processes in producing quantum dots is the major obstacle.

Composite Nanoparticles

Composite nanoparticles combine organic and inorganic materials to integrate the advantages of both systems, resulting in improved biocompatibility, stability, drug-loading capacity, and therapeutic efficacy (46). Among the most widely studied are lipid-polymer hybrid nanoparticles, which enhance drug delivery, cellular uptake, and circulation time, with promising applications in pancreatic, breast, and prostate cancers (47).

Other hybrid systems, including liposome-silica nanoparticles, carbon nanotube-chitosan composites, and metal-polymer nanocomposites, have demonstrated potential for targeted drug delivery, combination therapy, and hyperthermia-mediated cancer treatment (48). In addition, cell membrane-coated nanoparticles have emerged as promising biomimetic platforms that improve immune evasion, prolong circulation, and enhance tumor targeting, while dual-membrane coatings further improve

nanoparticle stability and performance (49).

Toxicity and Future Challenges of Nanoparticles in Cancer Therapy

Despite their remarkable potential in cancer diagnosis and treatment, nanoparticles raise important concerns regarding safety, biocompatibility, and environmental impact. Current evidence suggests that nanoparticle toxicity is largely dependent on their composition, physicochemical properties, and biological interactions rather than being an inherent feature of all nanomaterials. Certain nanomaterials, including carbon nanotubes, silver nanoparticles, and some metal-based nanoparticles, have been associated with adverse effects such as oxidative stress, DNA damage, inflammation, organ toxicity, and carcinogenicity in experimental studies (50). Similarly, silicate-based nanoparticles have been linked to fibrosis in the liver and lungs, while concerns regarding the accumulation of heavy metals in organs such as the liver and kidneys remain unresolved (50).

Conversely, not all nanomaterials exhibit significant toxicity. For example, graphene quantum dots have demonstrated relatively low toxicity and efficient elimination from the body, even at high doses in animal studies (15, 51). These findings highlight the importance of evaluating each nanoparticle system individually rather than generalizing toxicity across all nanomaterials.

Although numerous nanoparticle-based formulations have shown promising therapeutic outcomes, limited information is available regarding their long-term effects on human health and surrounding tissues. Future research should focus on understanding nanoparticle-induced inflammation, DNA interactions, organ-specific toxicity, biodistribution, and environmental consequences. Comprehensive toxicological assessments and molecular studies, including gene expression profiling, will be essential to ensure the safe and effective clinical translation of nanoparticle-based cancer therapies (52).

Conclusion

Nano-therapy has revolutionized cancer treatment and continues to offer new opportunities for improving therapeutic outcomes. This review highlights the role of nanotechnology in enhancing conventional cancer therapies through improved drug delivery, targeting, and therapeutic efficacy. Despite these advances, concerns regarding safety, biocompatibility, and environmental impact must be carefully addressed through comprehensive research and risk assessment.

Successful clinical translation will require multidisciplinary collaboration and a deeper understanding of nanoparticle interactions, biodistribution, and behavior within the tumor microenvironment. Future efforts should focus on developing next-generation nanotherapeutics incorporating emerging molecular agents such as kinase inhibitors, siRNA, mRNA, and gene-editing technologies. With continued advances in research and clinical development, nanotherapeutics are expected to play an increasingly important role in improving cancer management and patient survival.

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