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Applications of Carbon Nanotubes in the Field of Biomedicine

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Abstract

Carbon nanotubes, with their excellent mechanical, optical, and thermal properties as well as good biocompatibility, show broad application prospects in the field of biomedicine. This article systematically reviews its research progress in the fields of gene and drug delivery, biomedical imaging, cancer radiotherapy, and combined drug-photothermal therapy, with a focus on analyzing the innovative breakthroughs and existing challenges of core technologies such as targeted delivery, stimulus-responsive release, integrated diagnosis and treatment, and radiotherapy sensitization. Research shows that surface-modified carbon nanotubes can achieve targeted delivery and intelligent release of drugs and genes. Their optical and magnetic properties support integrated multimodal diagnosis and therapy. As radiotherapy sensitizers, they can enhance radiation energy deposition, and combined treatments can improve anticancer effects and reduce toxic side effects. Currently, there are still bottlenecks in its biosafety, large-scale production, and clinical translation. In the future, it is necessary to advance its clinical application in the biomedical field through material optimization, precise functional regulation, and the improvement of safety evaluation systems.

Keywords

carbon nanotubes, biomedicine, biomedical imaging, cancer treatment, combination therapy

1. Introduction

Carbon nanotubes are one-dimensional tubular materials formed by carbon atoms in sp^2 hybridization and can be regarded as seamless cylinders rolled from graphene sheets, with broad application prospects [1,2]. They are mainly divided into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) [1,2]. Single-walled carbon nanotubes are formed by curling a single layer of graphene, having a uniform structure and excellent performance, but are difficult to prepare [1]. Multi-walled carbon nanotubes are composed of multiple layers of graphene nested coaxially, which are more stable and can be produced in bulk, with broader applications [1]. Traditional biomedical materials have limitations in drug delivery efficiency, imaging resolution, and treatment accuracy, making it difficult to meet the needs of modern precision medicine and personalized treatment. This article explores the application value of carbon nanotubes in the biomedical fields such as gene and drug delivery, biomedical imaging, cancer radiotherapy, and combined drug-photothermal therapy, aiming to provide a theoretical basis and experimental reference for the development and clinical translation of novel nano-biomedical materials.

2. Applications in Gene and Drug Delivery

Carbon nanotubes, with their unique one-dimensional nanostructure, large specific surface area, and easy functionalization characteristics, have become highly potential carrier materials in the field of gene and drug delivery. Traditional drugs and gene delivery systems have problems such as poor targeting, low stability, easy degradation by enzymes, and significant side effects, which seriously restrict therapeutic effects. Leveraging their structural advantages, carbon nanotubes have been designed and developed into efficient, low-toxicity, and intelligent delivery systems, which help address the limitations of traditional delivery carriers and comprehensively improve the precision and safety of disease treatments. Their primary applications include targeted delivery, stimulus-responsive release, RNAi therapy, and the reversal of multidrug resistance in tumors.

2.1 Targeted Delivery

In terms of targeted delivery, by performing surface modification on carbon nanotubes, such as conjugating targeting ligands (antibodies, peptides, small molecules, etc.), active targeting of diseased tissues or cells can be achieved. Anurag Verma et al. pointed out that carbon nanotubes can serve as targeted drug delivery carriers, significantly increasing the drug accumulation concentration in tumor tissues through specific recognition of receptors on the surface of cancer cells, while simultaneously reducing the toxic side effects on normal tissues [2]. Chanchal Kiran Thakur et al. developed a ligand-conjugated multi-walled carbon nanotube targeted drug delivery system capable of achieving tumor-specific delivery of chemotherapeutic agents [3]. Compared to free drugs, this system significantly enhances antitumor efficacy, increasing the 24-hour tumor inhibition rate from 25.37% to 38.37%, with a tumor suppression rate reaching 80% after one week, while also reducing drug accumulation in normal tissues and improving treatment safety [3]. Furthermore, Mohammed Al zharani et al. utilized the delivery advantages of functionalized carbon nanotubes to cross the blood-brain barrier and constructed a brain-targeted nanodelivery system for neurodegenerative diseases [4]. This nanocarrier enables targeted accumulation in the brain via receptor-mediated endocytosis (RME) and adsorptive-mediated endocytosis (AME) [4]. It significantly improves drug deposition at lesion sites in glioma and neurodegenerative disease models, promotes hippocampal neuron adhesion and dendritic growth, and effectively enhances neural signal transmission, providing a novel strategy for targeted drug delivery and precision therapy of central nervous system disorders [4]. It can be seen that carbon nanotubes have excellent potential for targeted delivery, can significantly enhance accumulation in lesion areas, reduce systemic side effects, and provide a feasible carrier solution for targeted therapy of solid tumors and central nervous system diseases.

2.2 Stimulus Response

Stimuli-responsive delivery systems are an important direction for the application of carbon nanotubes in the biomedical field. In clinical chemotherapy, the non-specific systemic release of drugs readily causes damage to normal tissues and simultaneously reduces the effective drug concentration at the disease site, resulting in unsatisfactory therapeutic outcomes. Therefore, developing intelligent, responsive drug delivery systems targeting the tumor microenvironment is of great clinical significance for enhancing both targeting precision and safety. Utilizing the excellent functionalization properties of carbon nanotubes allows for precise and controlled drug release at the lesion site, effectively improving the therapeutic index and enhancing anti-tumor efficacy. Nabitabar Masoumeh et al. developed a stimulus-responsive dual-drug delivery system based on functionalized multi-walled carbon nanotubes for the co-delivery of curcumin (CUR) and methotrexate (MTX) [5]. Under acidic conditions of pH 4.4, this system cumulatively released approximately 60% of curcumin within 188 hours, whereas under physiological conditions of pH 7.4, only about 36% was released [5]. Additionally, under the action of protease K, methotrexate release reached up to 67% within 12 hours, demonstrating a significant dual response to both pH and enzymes [5]. This enables selective drug release in tumor acidic microenvironments and regions with high protease expression, effectively enhancing drug release efficiency at tumor sites and exhibiting good in vitro inhibitory effects on

MCF-7 breast cancer cells [5]. The above results clearly demonstrate that the pH/enzyme dual-responsive carbon nanotube drug delivery system can achieve precise and controlled drug release, significantly improving the efficacy of chemotherapy, and providing crucial experimental evidence for the design and development of multifunctional intelligent drug delivery systems.

2.3 Reversal of RNAi Resistance

In RNA interference (RNAi) therapy, carbon nanotubes act as efficient carriers for siRNA, protecting siRNA from degradation by nucleases in the body and facilitating its transmembrane delivery into cells. Yang Min et al. noted in their review that multi-walled carbon nanotubes functionalized via methods like amination can greatly improve the dispersibility and biocompatibility of carriers [6]. This modification helps enhance siRNA stability and cellular uptake efficiency, as well as strengthen gene silencing effects [6]. Accordingly, these functionalized carbon nanotubes hold great promise for gene therapy against hereditary diseases and cancer. [6]. At the same time, carbon nanotubes can effectively reverse the multidrug resistance (MDR) of tumor cells [2]. By co-delivering chemotherapeutic drugs and resistance-associated siRNA, carbon nanotubes are able to inhibit the drug efflux pump function in tumor cells, thereby restoring the sensitivity of cancer cells to chemotherapeutic drugs [2].

3. Applications in Biomedical Imaging

The unique optical, electrical, and magnetic properties of carbon nanotubes make them show great potential in the field of biomedical imaging. Traditional imaging technologies have problems such as limited information from a single modality, insufficient resolution, and difficulty in combining diagnosis and treatment, making them unable to meet the needs of precision medicine. However, if the integrative advantages of carbon nanotubes in multimodal imaging are fully utilized to develop highly sensitive and high-resolution imaging probes, it would help achieve real-time dynamic monitoring of disease, early diagnosis and treatment processes, especially showing outstanding performance in realizing 'diagnosis and treatment integration' and constructing multimodal imaging platforms.

3.1 Integrated Diagnosis and Treatment

Integrated diagnosis and therapy is a crucial direction in contemporary biomedical development. Carbon nanotubes can function simultaneously as diagnostic probes and therapeutic agents, offering an inherent advantage for combined diagnosis and treatment. Single-walled carbon nanotubes possess strong absorption and fluorescence emission properties in the near-infrared region, making them suitable for high-resolution fluorescence imaging. Under near-infrared light irradiation, carbon nanotubes efficiently convert light energy into heat through photothermal conversion, raising the local temperature to destroy tumor cells. The same system can simultaneously perform imaging localization, photothermal therapy, and efficacy assessment, achieving an integrated closed-loop for diagnosis and treatment. Liang chao et al. utilized the dual-modal imaging capabilities of PEGylated single-walled carbon nanotubes (SWCNTs-PEG) in the near-infrared II (NIR-II) region, combined with their strong near-infrared absorption properties, to construct an imaging-guided photothermal therapy platform [7]. This platform allows precise tracking of nanomaterial lymphatic metastasis from primary tumors to sentinel lymph nodes and enables simultaneous photothermal ablation of both primary lesions and metastatic lymph nodes [7]. Under near-infrared laser irradiation, this system can rapidly raise the temperature in tumor and metastatic lymph node regions to achieve an effective ablation temperature [7]. In the mouse 4T1 breast cancer model, this diagnostic and therapeutic strategy not only achieves precise imaging but also significantly inhibits tumor lung metastasis and greatly extends animal survival, accomplishing the synergistic integration of imaging diagnosis and photothermal therapy [7]. This integrated strategy effectively improves therapeutic precision, and efficacy can be evaluated through histological analysis and observation of survival [7]. The above results demonstrate that the integrated carbon nanotube diagnosis and treatment platform can simultaneously achieve precise tumor imaging and effective therapy, significantly reduce the risk of tumor metastasis, and offer a viable, innovative model for precise tumor diagnosis and treatment.

3.2 Dominated by Multimodal Imaging

In the field of multimodal imaging, single-walled carbon nanotubes are particularly extensively applied as optical nanomaterials and biosensors. Single-modal imaging is difficult to provide comprehensive disease information. Multimodal integration can improve diagnostic accuracy. Constructing multimodal imaging probes based on carbon nanotubes can obtain comprehensive information from the molecular, cellular, and tissue levels, significantly enhancing the accuracy and reliability of disease diagnosis. Rumi Acharya et al. confirmed in their review that single-walled carbon nanotubes can be used to construct fluorescence–Raman–photoacoustic multimodal imaging probes [8]. Their superior advantages include precise functionalization, near-infrared optical properties ranging from 900 to 1600 nm, as well as excellent high conductivity [8]. Such imaging probes possess outstanding in vivo performance in tumor models, realizing 3–5 cm deep tissue penetration, stable fluorescence signals against photobleaching, and a nearly fivefold increase in signal-to-noise ratio [8]. They also enable single-molecule real-time tracking of biomarkers related to cancer, infections and neurological disorders, thereby offering powerful nanotechnological foundations for early accurate diagnosis and multimodal image-guided treatment of diseases. [8]. Meanwhile, carbon nanotubes, owing to their functionalization capacity, high specific surface area, and excellent biocompatibility, can serve as a platform for constructing multimodal imaging probes, applicable to various imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET) [9]. This facilitates the acquisition of multidimensional information from the molecular to the tissue level, providing crucial support for early disease diagnosis and precise therapy [9].

4. Applications in Cancer Treatment

In the field of comprehensive cancer treatment, surgery, radiotherapy, and chemotherapy are the mainstream clinical treatment methods. However, issues such as tumor cell resistance, strong invasiveness and metastasis, significant treatment side effects, and insufficient precision remain key challenges restricting the clinical efficacy of cancer therapies. A single therapeutic approach often exhibits limited efficacy and may easily harm normal tissues, making it challenging to simultaneously achieve effective tumor suppression and safe treatment. Carbon nanotubes, with their unique one-dimensional tubular structure, excellent physicochemical properties, and advantages of high drug loading, high permeability, and targeted accumulation, can be used to construct multifunctional nanotherapeutic platforms. These platforms integrate multiple functions such as radiotherapy sensitization, photothermal therapy, photodynamic therapy, targeted drug delivery, and precise detection, demonstrating significant application potential in synergistic cancer therapy and comprehensive intervention.

Carbon nanotubes, particularly materials with high atomic numbers, can serve as ideal radiosensitizers, significantly enhancing the energy deposition of ionizing radiation such as X-rays in tumor tissues, mitigating tumor cell radiation resistance, and simultaneously integrating with optical therapy methods to achieve multi-mechanism synergistic anticancer effects. The review by Naief Mohammed Faiad et al. provides a detailed explanation of the mechanisms by which carbon nanotubes function in combined photothermal and photodynamic therapy [10]. Carbon nanotubes can accumulate in tumor tissues and, due to their needle-like structure, enhance tumor penetration [10]. Upon near-infrared light irradiation, they possess excellent photothermal conversion capabilities and simultaneously mediate photodynamic reactions to produce reactive oxygen species [10]. This dual mechanism synergistically destroys tumor cells and effectively improves antitumor efficacy [10].

In vivo animal experiments further corroborated the potential of carbon nanotubes in combined cancer therapy. Studies by Radzi Muhammad Redza Mohd et al. demonstrate that oxidized multi-walled carbon nanotubes (ox-MWCNTs), as effective hyperthermia agents, mediate the combined application of near-infrared hyperthermia (HT) and local hormone therapy, showing significant therapeutic effects in the mouse EMT6 breast cancer model, effectively eliminating breast tumors and promoting immune cell infiltration within the tumor microenvironment [11]. Studies by Siyang Gao et al. indicate that carbon nanotubes, as a nanoplatform for tumor diagnosis and therapy, can achieve 100% sensitivity and 98% specificity in serum detection of ovarian cancer [12]. Their multifunctional drug delivery system demonstrates a 24-hour drug release rate of up to 92.0%, while also exhibiting an ultra-high elastic modulus and excellent thermal and electrical properties, highlighting their broad potential in precise cancer diagnosis and targeted treatment [12].

A synthesis of existing research reveals that carbon nanotubes transcend the limitations of conventional single-modality cancer therapies, utilizing their unique physicochemical properties to enable the integration of multiple functions, including radiotherapy sensitization, phototherapy, targeted drug delivery, immunoregulation, and precise detection. The synergistic effect of multiple mechanisms can not only efficiently inhibit tumor proliferation and metastasis and reduce the adverse effects of treatment on the body, but also effectively compensate for the shortcomings of traditional cancer treatment regimens, providing a solid theoretical basis and experimental support for the optimization of clinical comprehensive cancer treatment strategies and the development of novel multifunctional nano-anticancer agents.

5. Application of Drug-Photothermal Combined Therapy

In clinical treatment, a single treatment modality often fails to achieve the desired anti-tumor outcomes, commonly facing issues such as limited efficacy and significant toxic side effects on normal tissues [12]. Therefore, multimodal synergistic therapy has become a crucial direction in the advancement of cancer treatment [12]. Carbon nanotubes, owing to their unique physicochemical properties, can function as multifunctional nanoplatforms combining drug delivery, imaging diagnosis, and therapeutic functions [12]. They can efficiently integrate chemotherapy with photothermal and photodynamic therapies, establishing a synergistically enhanced combination treatment system, thereby effectively improving tumor treatment outcomes and reducing adverse effects, and offering a new strategy for the precise treatment of mid- to late-stage cancers [12].

On this basis, by integrating drug delivery with photothermal therapy to establish a drug-photothermal combination treatment system, the therapeutic efficacy against tumors can be significantly enhanced. Research by Naief et al. highlights that carbon nanotubes possess both excellent photothermal conversion capabilities and favorable carrier characteristics [10]. Owing to their unique tubular structure and exceptionally high specific surface area, they can efficiently load and deliver anticancer therapeutic agents [10]. During the treatment process, the photothermal effect can effectively improve the tumor microenvironment and facilitate the deep tissue penetration and accumulation of carbon nanotubes [10]. By leveraging their near-infrared light-responsive properties, carbon nanotubes can exert a potent photothermal effect to destroy tumor cells and, when combined with loaded drugs, generate a synergistic antitumor effect [10]. This combined therapeutic approach not only enhances overall anti-cancer efficacy, but also allows for a reduction in the dosage of individual treatments, decreases adverse biological toxicity, and offers new research insights and application directions for minimally invasive, precise drug-photothermal synergistic therapy for cancer [10].

6. Conclusion

Carbon nanotubes, owing to their unique one-dimensional nanostructure, outstanding physicochemical properties, and excellent biocompatibility, exhibit irreplaceable value in biomedical applications. As a carrier for gene and drug delivery, following targeted modification and stimulus-responsive design, it can achieve precise delivery and controlled release of drugs and genes, effectively reverse tumor multidrug resistance, and significantly enhance therapeutic efficacy and safety. In the field of biomedical imaging, carbon nanotubes can be employed to develop high-resolution multimodal imaging probes and integrated diagnosis-treatment platforms, facilitating early tumor detection, precise therapy, and real-time monitoring of therapeutic outcomes, thereby providing essential technological support for precision medicine. In cancer radiotherapy, carbon nanotubes act as highly efficient radiosensitizers, enhancing tumor radiosensitivity through both physical and chemical sensitization mechanisms, and thereby reducing the required radiotherapy dose and the damage to normal tissues. In the field of combination therapy, carbon nanotubes can integrate chemotherapy, photothermal therapy, and radiotherapy to achieve multi-modal synergistic effects, substantially enhancing the treatment outcomes of advanced-stage solid tumors and reducing the toxic side effects associated with monotherapy.

Although carbon nanotubes still confront numerous challenges in biosafety, scalable production and clinical translation, their in vivo metabolic behaviors and long-term biocompatibility have not been fully elucidated. Potential toxicity and immunogenicity risks require systematic evaluation. The uniformity and stability of large-scale production are difficult to control, and batch-to-batch variations affect application outcomes. Further refinement is needed in in vivo targeting efficiency, degradation performance, and integration with clinical standard systems. With the continuous advancement of materials science and biomedical technology, through material structure optimization, the development of biodegradable carbon nanotubes, precise functional regulation, and the establishment of safety evaluation systems—while also promoting animal experiments and preclinical studies—and balancing material performance with biocompatibility, carbon nanotubes are poised to achieve significant breakthroughs in fields such as gene therapy, precision oncology, and the treatment of central nervous system disorders. They will become a core representative of the next generation of biomedical materials, driving the development of the biomedical field toward greater precision, efficiency, and safety.

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