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Potential Application of Janus Particles in the Fields of Tumor Treatment

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Abstract: Janus particles are nanoparticles that exhibit two distinct surface properties, with unique physicochemical characteristics and application potential. Janus particles are widely discussed and used in the medical field due to their special anisotropy. It is proposed as a new method of drug delivery to overcome the limitations of traditional drug delivery methods. Janus particles also have potential in application for photothermal combined therapy since they can deliver different required structures to the tumor site for treatment. Although it has shown the potential to control motion in physiological environments, very little is known about the motion ability of Janus particles. This article primarily discusses the motion mechanisms of different types of particles and demonstrates their potential applications in cancer treatment and care. Examples include targeted drug delivery, point-of-care testing (POCT), and photothermal treatment. It highlights the potential of particles in future tumor treatments. The specific applications and preparation methods of JPs still require further research.

Keywords: Tumor treatment, Janus particles, Photothermal therapy

1. Introduction

Janus particles (JPs) [1-3] are micro/nano particles with two distinct sides, each with different chemical and physical properties, which give them unique functionalities. The name comes from the ancient Roman god Janus, who has 2 different faces, symbolizing the dual nature of these particles. Since the two sides of the JP have different properties, a different reaction takes place on either side and one propulsive force results giving the JP a specific direction of propulsion. JPs offer new concepts in nanomachine construction and biosensors. They are now widely used for drug delivery and construction of biosensors [4,5]. In this review, we have examined the potential applications of Janus particles across various domains of tumor therapy, encompassing tumor detection, targeted drug delivery, and combined photothermal treatment. This essay expands JPs' knowledge boundaries in cancer treatment, providing a scientific rationale and references to advance biomedical technologies and oncological therapies.

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2. Janus particles in tumor treatment

Due to the complexity of cancer cells, it is often difficult for a single treatment to effectively kill the tumour tissue. The synergistic use of multiple therapeutic agents can effectively enhance therapeutic effect and reduce side effects, which is a current hotspot in tumour therapy [6]. JPs, owing to their unique properties, have shown great potential for tumour-synergistic therapy.

3. Janus particles in clinical detection of tumors

The anisotropy of JPs renders them excellent biosensors [7]. Modifying one surface of JP with capture molecules (e.g., antibodies, nucleic acid aptamers) enables specific binding to target biomarkers. In contrast, the opposite surface is modified with signal reporting molecules (fluorescent dyes, enzymes) [8] or magnetic substances. This allows detection of a small number of markers in large sample volumes and also quick separation and enrichment. Therefore, JP has attracted much attention and research in the field of biodetection. For patients with early-stage cancer, circulating tumour DNA (ctDNA), exosomes, or specific proteins (carcinoembryonic antigen CEA, alpha-fetoprotein AFP) [9] are present at extremely low concentrations, posing significant challenges for capture and detection. Biosensors fabricated using JP hold promise for detecting low-concentration biomarkers elusive to conventional methods, thereby enabling earlier cancer detection.

The fluorescence biosensor developed by JPs offers high sensitivity, strong anti-interference properties, rapid response, and simple detection procedures [10].

Yang et al. constructed a Janus 3D DNA nanomachine for simultaneous detection and imaging of dual miRNAs in cancer cells [11]. Compared with existing methods for imaging microRNAs (miRNAs) that use nanoparticle components, the proposed approach has been shown to eliminate "false-positive" results effectively and to reduce the detection limits for sensitive analyses to 3.5 × 10-13 M and 4.8 × 10-13 M for miRNA-21 and miRNA-155, respectively.

At the same time, even in the detection of only one kind of miRNA by using Janus nanoparticles as a carrier loaded with two signal probes at fixed concentrations, the fluorescence intensity was further enhanced. Fluorescence imaging has proven capable of visualizing low concentrations of cancer-specific microRNAs more accurately than conventional methods based on fluorescence in situ hybridization [1].

4. Janus particles as a drug delivery system

JPs play a vital role in drug delivery due to their multifunctionality, stemming from the integration of two distinct materials. Through external magnetic fields and other control methods, JPs can precisely deliver drugs to specific locations. This precision is particularly crucial in cancer treatment, as it minimises damage to healthy tissue during the therapeutic process.

4.1. Active targeted drug delivery

The Js Particle double layer provides for the attachment of various specific ligands or surface modifications. Apart from antibodies or ligands binding to tumor markers, magnetic or heavy metal components can be added on one side for magnetic resonance or optical localization and guidance while the other side contains drug release structures. In this manner, targeted and controlled drug delivery real-time monitoring as well as evaluation of therapeutic effectiveness is enabled [12].

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4.2. GSH/ROS-responsive drug release

JPs may incorporate multiple stimulus-response mechanisms to enable recognition of the tumour microenvironment and drug release. For instance, Zhang et al. developed a drug delivery platform that responds to lactate produced by cancer cells via the Warburg effect [13]. Similarly, tumour cell characteristics may be leveraged to construct ROS-responsive drug release structures on the JP surface. Due to metabolic abnormalities, tumour tissues exhibit a strongly reducing environment within tumour cells.

Such as glutathione (GSH) (2–10 mmol/L), are over 1,000 times higher than extracellular GSH levels (2–20 μmol/L) and four times higher than in normal cells. In drug-resistant tumour cells, GSH concentrations may even be tenfold higher [14]. Consequently, this disparity in intracellular and extracellular reducing potential offers an avenue for designing ROS-responsive targeted drug delivery systems.

4.3. Janus particles in photothermal/chemotherapeutic treatment

Janus particles exhibit superior performance compared to conventional monofunctional nanomaterials in multimodal cancer therapy, owing to their unique structure, which features distinct chemical or physical properties on opposite sides [15]. In integrated photothermal-chemotherapy, JPs enhance the efficacy of combined photothermal treatment by leveraging their dual-surface functionalities.

Most notably, by locating the photothermal treatment zone and drug release zone on separate sides, JPs minimize possible interference between the two materials thereby boosting combined treatment efficacy. Functional compartmentalization also provides greater design flexibility for therapeutic structures allowing an optimized arrangement of light-absorbing materials to enhance light absorption and scattering efficiency. Integration of photothermal therapy with chemotherapy enhances drug delivery [16]. The photothermal effect disrupts tight junctions within tumour tissue, enabling easier drug penetration into the tumour.

5. Challenges of Janus particles in the field of tumor treatment

Undoubtedly, Janus particles hold immense potential for application in cancer therapy. However, JPs‘ practical use in humans presents specific challenges and risks. Heavy metals and certain inorganic compounds possess inherent toxicity [17]. At the same time, the human body's capacity to metabolise and eliminate Janus particles remains urgently unassessed, posing a risk of accumulation.

Secondly, under current conditions, the industrial-scale production of highly uniform Janus particles remains challenging [18], significantly limiting the application and clinical translation of JPs.

Finally, JPs may be recognised as antigens by the immune system [17] within the human body, triggering phagocytosis by macrophages. This issue requires resolution by limiting JPS particle size and implementing surface modifications (PEG, etc.).

6. Conclusion

To conclude, the study discloses potential exploits of Janus particles as a multi-functional platform in oncology. That is basically due to its two distinct surface properties that address, at a very advanced level, the limitations imposed by traditional nanomedicine- based solutions. Its application

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ranges from increasing sensitivity for point-of-care testing (POCT) toward early cancer biomarkers to high precision active targeted drug delivery and separation of therapeutic functional zones enabling synergistic photothermal chemotherapy wherein physical separation has been implemented between thermal and chemical zones inside one single particle [19]. Anisotropy introduces into JP design flexibility and spatial control on a scale impossible with homogeneous nanoparticles. However, several critical challenges must be addressed before clinical translation. The long-term biocompatibility and metabolic pathways of inorganic JP components remain insufficiently understood, posing potential risks of systemic toxicity. Furthermore, the current synthesis methods often struggle with scalability and batch-to-batch consistency. To overcome these hurdles, future research should prioritize the development of biodegradable, bio-based Janus materials and the optimization of high-throughput fabrication techniques, such as microfluidics.

Looking ahead, the integration of "active motion" capabilities will be a key research frontier, enabling JPs to navigate through dense tumor extracellular matrices more effectively. Additionally, focusing on biomimetic surface modifications, such as leukocyte or red blood cell membrane coating [19], will be essential to evade immune clearance. By combining intelligent navigation, immune evasion, and multimodal therapy, Janus particles are poised to redefine the landscape of next-generation personalized cancer treatment.

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