Biomedical Data Science
2025, VOL. 5, NO. 1, 45-48
DOI: 10.47297/wspbdsWSP2752-630510.20250501

New Progress of Nanotechnology in the Diagnosis and Treatment of Oral Cancer

Yi Zhang

Stomatology major, Northwest University for Nationalities, Gansu, Lanzhou, 730030, China

ABSTRACT
Oral cancer is a malignant tumor of the head and neck with rising morbidity and mortality, and traditional treatments often have limitations such as functional damage and side effects. This paper reviews the latest research progress of nanotechnology in the diagnosis and treatment of oral cancer. With its unique physical and chemical properties and ultra-small size effect, nanotechnology shows significant advantages in tumor diagnosis and treatment. In terms of diagnosis, nanotechnology uses highly sensitive biosensors to detect biomarkers, develop new nanomaterials to achieve efficient enrichment of circulating tumor cells, and use nanoprobes to detect cell core acids. In terms of treatment, multi-stage nano-drug delivery systems significantly improve the bioavailability and specificity of drugs through passive and active targeting mechanisms; photodynamic therapy and magneto-thermotherapy based on nanomaterials achieve accurate treatment of tumors. Although nanotechnology has made remarkable progress in the field of diagnosis and treatment of oral cancer, there are still many challenges in large-scale production, safety evaluation and clinical transformation, which need further in-depth research and standardized application.

KEYWORDS
Oral cancer; Nanotechnology; Drug delivery system; Circulating tumor cells; Photodynamic therapy

1 Introduction

Oral cancer is a common malignant tumor of the head and neck, mainly including oral squamous cell carcinoma. The incidence of oral cancer is increasing year by year, especially in areas with high incidence of smoking, drinking and human papillomavirus (HPV) infection. Oral cancer poses a serious threat to human health. While traditional treatments such as surgery, radiotherapy and chemotherapy control tumors, they are often accompanied by functional damage, radiation side effects and chemotherapy resistance, which limit the therapeutic effect and reduce the quality of life of patients. With the rapid development of biotechnology and material science, nanotechnology provides a new solution for the diagnosis and treatment of oral cancer.

Nanotechnology can significantly improve the targeting and bioavailability of drugs in tumor sites by making use of ultra-small size, high surface area and controllable physical and chemical properties, so as to reduce normal tissue damage and reduce side effects. Nanotechnology-based drug delivery systems, early cancer diagnosis tools and treatments have shown great potential in the research and clinical application of oral cancer. At the same time, the innovative applications of nanomaterials in the detection of cancer biomarkers, capture of circulating tumor cells (CTC), photodynamic therapy and magnetothermotherapy also provide a new direction for the accurate treatment of oral cancer. Therefore, the research progress of nanotechnology in the diagnosis and treatment of oral cancer has become one of the hotspots in the field of tumor therapy, which brings new hope for improving the survival rate and quality of life of patients with oral cancer.

2 Overview of nanotechnology

Nanoparticles are solid colloidal particles carefully designed by natural, synthetic or semi-synthetic polymers, which can carry drugs in a variety of ways, such as dissolving, embedding, wrapping or attaching drugs to the matrix of nanoparticles. This design enables nanoparticles to serve as both a repository of drugs and an efficient drug delivery carrier to accurately deliver therapeutic drugs to targets. At present, nano-preparations show significant advantages in the treatment of oral cancer, which can not only improve the bioavailability and distribution of drugs in the tumor site, but also shorten the treatment time, enhance drug targeting and reduce damage to healthy tissues.

Nanoparticles play a role through passive and active targeting mechanisms. Passive targeting makes use of the high permeability and long retention effect of tumor tissue (EPR effect) to make nanoparticles naturally enrich in the tumor area [1]. Active targeting further improves the accuracy of drug delivery by surface modification of specific molecules (such as antibodies or peptides). These innovative applications solve the problems of low availability and non-specific distribution of traditional oral drugs, and reduce the toxicity of chemotherapeutic drugs.

In the early detection of cancer, nanotechnology can effectively detect cancer biomarkers and circulating tumor cells

by virtue of its high sensitivity and specificity, and improve the accuracy of early diagnosis. At the same time, the application of nanoparticles in in vivo imaging is helpful to accurately locate the cancerous region and promote the implementation of personalized therapy.

With the progress of technology, nanotechnology will play a greater role in the whole process of cancer diagnosis and treatment, providing new opportunities for improving the prognosis of patients and promoting accurate medical care.

3 Application of nanotechnology in the diagnosis of oral cancer

3.1 nanoparticle labeled biosensor

Cancer biomarkers are molecules that can be detected in blood, tissue fluids or other body fluids, usually secreted by the body or cancer cells during the occurrence of cancer, including secretory proteins, cell surface proteins, carbohydrates or nucleic acids (such as circulating tumors DNA, miRNA, etc.) [2]. Biosensors can enhance the targeting and sensitivity to specific molecules by combining nanoparticles to meet the high precision requirements of cancer molecular diagnosis.

Professor Chen Ming of Army military Medical University has developed a self-feedback tetrahedral entropy driven DNA circuit intelligent nano diagnosis and treatment platform based on double miRNAs guidance. This innovative platform can not only detect intracellular carcinogenic miRNAs, but also achieve accurate targeted therapy by releasing tumor suppressor miRNAs. The nano-diagnosis and treatment platform consists of a DNA tetrahedron containing an entropy-driven DNA loop. In order to achieve highly sensitive detection of trace amounts of intracellular miRNA, the researchers used the entropy of DNA nano-assembly technology to drive the DNA circuit, the core of which is a programmed nucleic acid self-assembly process, which relies on the heat obtained by the system entropy in DNA hybridization reaction to push the detection. This process is carried out under isothermal conditions without the participation of enzymes and does not change any covalent bonds in cells, thus ensuring biosafety.

The signal is amplified by entropy-driven loop circuit, and the platform can detect carcinogenic miRNAs hypersensitively. Then, using DNA tetrahedron as an efficient transmembrane carrier, the entropy-driven DNA loop is accurately delivered to cancer cells. This platform can not only detect carcinogenic miRNAs, but also release tumor suppressor miRNAs synchronously and realize two-way gene regulation, so as to complete the integration of tumor diagnosis and treatment [3]. This innovative nano-diagnosis and treatment technology provides a new possibility for the accurate treatment of cancer.

3.2 nanoparticles for detection of circulating tumor cells (CTC)

In the process of metastasis and spread of cancer, cancer cells first invade the surrounding tissue from the primary tumor, and then enter the microvessels (infiltration) or lymphatic system of the blood.Cancer cells survive through the blood and further transfer to the microvessels of the distal tissue, then detach from the bloodstream (extravasation) and survive in the microenvironment of the distant tissue. This process provides a suitable environment for the formation of secondary tumors [4]. Early detection of metastatic cancer cells in circulation, namely circulating tumor cells (CTC), is of great significance for the prognosis and diagnosis of cancer.

The detection of CTC can provide valuable information for the molecular characteristics of tumors in a minimally invasive way, thus helping to guide personalized treatment.Studies have shown that cellular pseudopodia can be formed on the surface with nanostructures, which enhances the local topological interaction between cancer cells and nanostructured substrates, thus contributing to the enrichment of CTC. Because of its large surface area to volume ratio, nanomaterials can efficiently adsorb targeted ligands and identify specific fractions on the surface of cancer cells, which makes the separation process of CTC with high specificity and recovery, and greatly improves the sensitivity of detection.

A variety of nanomaterials have been used for CTC detection, such as magnetic nanoparticles (MINPs), gold nanoparticles (AuNPs), quantum dots (QDs), nanowires, nanorods, silicon nanorods, carbon nanotubes, dendrimers, graphene oxide and polymers [5]. These materials can effectively improve the sensitivity and specificity of CTC detection devices, and greatly promote the accuracy of early diagnosis and prognosis of cancer. Through the application of these nanomaterials, CTC detection is expected to become an important tool for predicting cancer progression and personalized treatment decisions in the future.

3.3 nanoparticles as intracellular nucleic acid biosensor

It is a feasible and effective method to use oligonucleotides to hybridize with fluorophores labeled complement modified gold nanoparticles probe as transfection agent and intracellular "nanoparticles" to detect mRNA in living cells. This "nano-flare" technique overcomes the problem of insufficient sensitivity and stability of traditional biological probes used in cells. Nano-flares show high signal-to-noise ratio and are highly sensitive to the change of the number of RNA

transcripts in cells, and can monitor the dynamic changes of gene expression in cells in real time [6].

In addition, with its high positioning accuracy and dense surface oligonucleotide coating, nanofibers can enter cells efficiently without the use of cytotoxic transfection agents. This property makes nanofibers have significant advantages in the detection of intracellular mRNA, which can not only avoid potential damage to cells, but also provide reliable mRNA detection results [7]. This nanotechnology provides an efficient and safe tool for real-time monitoring of gene expression in living cells, and is expected to be widely used in gene research, disease diagnosis and treatment monitoring in the future.

4 Application of nanotechnology in the treatment of oral cancer

4.1 nanometer drug delivery system

The nanoparticle system shows excellent drug carrier ability and site-specific drug accumulation performance in tumor therapy. Compared with the traditional free drug preparations, the nanoparticle-based drug delivery system showed higher drug solubility, longer drug cycle time and more significant efficacy in preclinical studies. Nanoparticles can be used as ideal carriers of chemical preventive compounds, nucleic acid drugs and diagnostic agents, and are widely used in the treatment of cancer. A significant advantage of the nanomedical platform is its versatility, which can overcome continuous biological barriers in the human body (such as the isolation of mononuclear phagocytic systems) through fine design, and these barriers often limit the effectiveness of traditional drug delivery [8].

The first generation of nanoparticle drug delivery system mainly relies on passive targeting to achieve the natural accumulation of drugs in the tumor site through enhanced permeability and retention effect (EPR effect). With the development of technology, the second-generation nano-drug delivery system further improves tumor targeting and drug release accuracy by adding active targeting functions (such as modified monoclonal antibodies) and stimulus response mechanisms (such as sensitivity to pH or anoxic environment).

In the third generation, the nanoparticle drug delivery system is more complex, using the design of multi-stage nano-carriers. This multistage system usually consists of the first stage mesoporous silicon particles (S1MIPs) and the second stage nanoparticles embedded in it.

Through intravenous injection, S1MIPs can interact with endothelial cells and release embedded second-level nanoparticles directly into the tumor stroma [9]. This hierarchical delivery strategy can not only improve the efficiency of drug accumulation in the tumor, but also reduce the damage to normal tissue, thus improving the specificity and safety of treatment [10]. This technique provides a more accurate drug delivery tool for cancer treatment in the future, and is expected to significantly improve the therapeutic effect and prognosis of patients in clinical application.

4.2 Photodynamic therapy

In photodynamic therapy (PDT), it is necessary to select a photosensitizer that can selectively accumulate in oral cancer cells. This photosensitizer is usually injected into the body through intravenous injection, or local application directly acts on the swollen area. After the photosensitizer accumulates in the cancer cell, a specific wavelength of light source (such as a laser) is used to illuminate the tumor area and excite the photosensitizer to a high-energy state. In this state, the photosensitizer reacts with oxygen molecules in the tissue to produce highly active singlet oxygen and other reactive oxygen species. These reactive oxygen species have direct cytotoxic effects on tumor cells by causing cell membrane damage, protein degeneration and DNA damage, resulting in cancer cell death [11].

PDT can not only kill cancer cells directly through reactive oxygen species, but also activate the body's immune system to produce a local immune response to help remove residual cancer cells and reduce the possibility of recurrence. By accurately controlling the irradiation area and dose of the light source, PDT can effectively avoid damage to the surrounding healthy oral mucosa and tissue, and minimize the side effects of treatment [12]. This accurate local treatment makes PDT an effective and relatively safe choice for the treatment of oral cancer, especially for patients who are not suitable for large-scale surgery.

4.3 Magnetothermal therapy

Nanoparticles have the power to convert non-ionized electromagnetic radiation generated by external energy (such as laser) into thermal energy, thus inducing cell apoptosis locally. This process depends on the phenomenon of plasmon resonance, in which nanoparticles produce local high temperature under a specific wavelength of light, which directly exerts thermal stress on tumor cells. This local hyperthermia can not only destroy the membrane structure and protein function of tumor cells, but also trigger the mechanism of intracellular apoptosis, which eventually leads to the death of tumor cells.

Among them, magnetic nanoparticles such as gold nanoparticles shell have received extensive attention in this field.

Gold nanoparticles have been used in clinical trials to explore photothermal ablation techniques for the treatment of many types of tumors, including oral squamous cell carcinoma, because of their excellent photothermal conversion efficiency and biocompatibility. By using laser targeting to irradiate tumor areas containing these nanoparticles, cancer cells can be precisely heated and killed with minimal damage to surrounding healthy tissue [13].

This kind of photothermal therapy based on nanoparticles has great potential in tumor therapy, especially in tumors that are not suitable for traditional treatment or difficult to be resected by surgery, it is expected to become an effective alternative therapy. With the further optimization of correlation technology, the application of nanoparticles in tumor therapy is expected to be more widely promoted and applied in clinic.

5 Conclusion

Although remarkable progress has been made in the diagnosis and treatment of oral cancer based on nanotechnology, there are still many challenges to accelerate its clinical application. First of all, the reliability and stability of nanoparticles must be quantitatively evaluated to ensure their clinical consistency and controllability. Secondly, the large-scale production of nanoprobes with high sensitivity, long-term storage stability and reasonable cost is still a key problem. Due to the differences in the shape, size, composition, charge and surface coating of nanoprobes, the differences between batches in the production process can not be avoided. Therefore, simplifying the synthesis steps is a necessary measure to reduce these changes [14]. Another important issue is the potential toxic reactions that may be caused by systemic administration of nanoparticles. In order to ensure the safe application of nanotechnology, the safety of nanomaterials must be comprehensively evaluated in preclinical and clinical studies, and effective risk management and mitigation strategies must be formulated. In addition, regulators need to develop clear guidelines and standards to ensure the safety and effectiveness of nanotechnology in the treatment of oral cancer. These measures will help to promote the transformation of nanotechnology from laboratory research to clinical application, and ultimately bring safer and effective treatment options for patients.

References

[1] Pei J, Natarajan PM, Umapathy VR, Swamikannu B, Sivaraman NM, Krishnasamy L, Palanisamy CP. Advancements in the Synthesis and Functionalization of Zinc Oxide-Based Nanomaterials for Enhanced Oral Cancer Therapy. Molecules. 2024, 29(11):2706.

[2] Guérin M, Lepeltier E. Nanomedicines via the pulmonary route: a promising strategy to reach the target? Drug Deliv Transl Res. 2024, 14(8): 2276-2297.

[3] Cui L, Pi J, Qin B, Cui T, Liu Z, Lei L, Wu S. Advanced application of carbohydrate-based micro/nanoparticles for rheumatoid arthritis. Int J Biol Macromol. 2024, 269(Pt 1):131809.

[4] Das U, Kapoor DU, Singh S, Prajapati BG. Unveiling the potential of chitosan-coated lipid nanoparticles in drug delivery for management of critical illness: a review. Z Naturforsch C J Biosci. 2024, 10;79(5-6):107-124.

[5] Zhang Y., Li M., Gao X., et al. Nanotechnology in cancer diagnosis: progress, challenges and opportunities. Journal of Hematology & Oncology. 2019, 12(1):137.

[6] Chen W. H., Lecaros R. L., Tseng Y. C., et al. Nanoparticle delivery of HIF1α siRNA combined with photodynamic therapy as a potential treatment strategy for head-and-neck cancer. Cancer Letters. 2015, 359(1):65-74.

[7] Jain S., Hirst D. G., O'Sullivan J. M. Gold nanoparticles as novel agents for cancer therapy. The British journal of radiology. 2012, 85(1010): 101-113.

[8] Gharat S. A., Momin M., Bhavsar C. Oral Squamous Cell Carcinoma: Current Treatment Strategies and Nanotechnology-Based Approaches for Prevention and Therapy. Critical reviews in therapeutic drug carrier systems. 2016, 33(4):363-400.

[9] Parkhe VS, Tiwari AP. Gold nanoparticles-based biosensors: pioneering solutions for bacterial and viral pathogen detection-a comprehensive review. World J Microbiol Biotechnol. 2024, 40(9):269.

[10] Choramle M, Verma D, Kalkal A, Pradhan R, Rai AK, Packirisamy G. L-Cysteine functionalized magnetite nanoparticle adorned Ti3C2-MXene nanohybrid based screen printed immunosensor for oral cancer biomarker detection. Anal Methods. 2024, 16(29):4938-4950.

[11] Ntadambanya A, Pernier J, David V, Susumu K, Medintz IL, Collot M, Klymchenko A, Hildebrandt N, Le Potier I, Le Clainche C, Cardoso Dos Santos M. Quantum Dot-Based FRET Nanosensors for Talin-Membrane Assembly and Mechanosensing. Angew Chem Int Ed Engl. 2024, e202409852.

[12] Chu X, Zhong X, Zang S, Wang M, Li P, Ma Y, Tian X, Yang Y, Wang C, Yang Y. Stem cell-like circulating tumor cells identified by Pep@MNP and their clinical significance in pancreatic cancer metastasis. Front Oncol. 2024, 14:1327280.

[13] Kefayat A, Sartipzadeh O, Molaabasi F, Amiri M, Gholami R, Mirzadeh M, Shokati F, Khandaei M, Ghahremani F, Poursamar SA, Sarrami-Forooshani R. Microfluidic System Consisting of a Magnetic 3D-Printed Microchannel Filter for Isolation and Enrichment of Circulating Tumor Cells Targeted by Anti-HER2/MOF@Ferrite Core-Shell Nanostructures: A Theranostic CTC Dialysis System. Anal Chem. 2024, 96(11):4377-4384.

[14] Szymaszek P, Tyszka-Czochara M, Ortyl J. Application of Photoactive Compounds in Cancer Theranostics: Review on Recent Trends from Photoactive Chemistry to Artificial Intelligence. Molecules. 2024, 29(13):3164.