Abstract

Cancer remains one of the leading causes of human mortality, resulting in nearly ten million deaths each year. According to global statistics, approximately one in ten people die from cancer, and this proportion continues to rise. The high incidence and fatality rates of cancer impose a heavy economic burden on families and public healthcare systems and represent a major barrier to the extension of human lifespan. Although conventional treatment modalities—including surgery, radiotherapy, chemotherapy, endocrine therapy, and immunotherapy—have achieved certain efficacy in early-stage or non-metastatic tumors, challenges such as drug resistance, recurrence, and metastasis persist, keeping the mortality rate alarmingly high. Therefore, developing more effective therapeutic strategies to achieve complete tumor eradication, suppress metastasis, and prolong patient survival remains of great significance.

In recent years, photothermal immunotherapy (PTI) which integrates photothermal therapy (PTT) with immunotherapy—has emerged as a highly promising strategy for the treatment of malignant tumors. PTT employs materials with high photothermal conversion efficiency to convert near-infrared (NIR) light energy into heat, thereby enabling localized ablation of tumor tissues. However, even materials with excellent photothermal properties, such as carbon nanotubes and liquid metals, suffer from poor solubility, strong aggregation tendency, and lack of efficient tumor-targeted delivery, which greatly hinder their biomedical applications. To address these challenges, biomimetic membrane modification has been proposed as an effective approach. Coating photothermal materials with biologically derived membranes rich in phospholipids and proteins (e.g., cell membranes or plasma membranes) can markedly improve their dispersibility and biocompatibility, while conferring immune evasion and active tumor-targeting capabilities—thereby enhancing their therapeutic performance and in vivo stability.

Furthermore, the construction of biomimetic nanoplatforms provides new opportunities for multimodal synergistic therapy. When combined with chemotherapy, these platforms can improve the selective delivery and antitumor efficacy of drugs. When integrated with

immunotherapy, they can effectively activate and sustain systemic antitumor immune responses, induce long-term immune memory, and consequently inhibit tumor recurrence and metastasis. Based on these insights, This dissertation focuses on the construction of multifunctional nanoplatforms based on biomimetic strategies, aiming to enhance tumor targeting, therapeutic efficacy, and immune activation through photothermal–immunotherapy synergy. A series of multimodal nanocomplexes derived from carbon-based and liquid metal (LM) materials were systematically developed for effective cancer treatment.

In the first part, a tumor cell–membrane–coated biomimetic carbon nano horn (CNH) nanoplatform loaded with paclitaxel (PTX) was fabricated to achieve combined photothermal therapy, chemotherapy, and immunotherapy for colorectal cancer. The platform exhibited excellent photothermal conversion efficiency under near-infrared irradiation, enabling light-controlled drug release and precise tumor ablation. Moreover, the membrane coating markedly improved colloidal stability, immune evasion, and tumor-targeting capability, while its intrinsic components helped activate certain antitumor immune responses.

In the second part, a bacteria-membrane–wrapped liquid metal (LM) nanosystem was developed, which effectively improved LM dispersibility and reduced aggregation. Taking advantage of the bacterial membrane's adjuvant properties, this system significantly amplified immune activation and enhanced photothermal performance. The nanoplatform promoted dendritic-cell maturation and antigen presentation, strengthened systemic antitumor immunity, and achieved efficient tumor eradication and long-term immune protection through photothermal–immunomodulatory synergy.

In the third part, a whole-blood–camouflaged LM nanoplatform (B–LM–DMX–αCD25) was designed by co-loading the STING agonist DMXAA and anti-CD25 antibody for efficient photothermal immunotherapy of triple-negative breast cancer (TNBC). This multifunctional system integrated Treg depletion, PTT-induced immunogenic cell death (ICD), and STING activation within a single nanoplatform, achieving cascade amplification of antitumor immunity. The coordinated mechanism effectively reprogrammed the immunosuppressive tumor microenvironment, resulting in complete regression of orthotopic TNBC and significant

inhibition of lung metastasis.

In summary, this dissertation proposes a systematic design strategy for biomimetic functional nanoplatforms that integrate photothermal effects with immune modulation, providing a new theoretical and technological foundation for the development of efficient, controllable, and low-toxicity cancer therapies.

Keywords: Cancer therapy, Biomimetic nanoplatforms, Photothermal immunotherapy, Carbon nanohorns; Liquid metal nanoparticles.