Original Research Article

Intelligent patrol and targeted therapy integrated breast cancer defense nanorobot: Technology, application, and prospects

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Abstract: Breast cancer, with the highest morbidity and mortality among women globally, presents significant challenges in early diagnosis and precision treatment. This paper proposes a breast cancer defense nanorobot integrating intelligent patrol and targeted therapy functions. The nanorobot incorporates biosensors, targeting technology, drug delivery systems, and intelligent navigation control, enabling highly sensitive identification, precise localization, and controlled drug release. Structurally, it utilizes DNA origami and biodegradable materials for biocompatibility and stability. Functionally, it combines FRET sensing with CRISPR gene editing to enhance diagnostic accuracy and therapeutic efficacy. Through multidisciplinary collaboration, the system underwent full-chain development from design to experimental validation. Results demonstrate excellent motility, targeting ability, and therapeutic effect, showing broad application prospects in breast cancer treatment.
Keywords: breast cancer; nanorobot; intelligent patrol; targeted therapy; biosensor; CRISPR; FRET

1. Introduction

Breast cancer is a malignant tumor posing serious threats to women's health globally. According to the International Agency for Research on Cancer, there were 2.3 million new cases worldwide in 2022[1], accounting for one-quarter of all female cancer cases, and 670,000 deaths, representing over fifteen percent of female cancer deaths. One in twenty women globally is diagnosed with breast cancer, and one in seventy may die from it. By 2050, cases are projected to increase by nearly forty percent, with more significant growth in low-income countries. Incidence rates are highest in Australia, New Zealand, North America, and Northern Europe, while mortality-to-incidence ratios exceed fifty percent in low Human Development Index countries compared to less than twenty percent in high-index countries, reflecting significant disparities in diagnosis and treatment.

The harm of breast cancer is multifaceted. Physiologically, cancer invasion impairs organ function, with metastasis to lymph nodes, lungs, liver, bones, and brain causing severe symptoms. Psychologically, patients endure fear, anxiety, and depression. Economically, treatment costs burden families and society. Thus, exploring effective prevention and treatment methods is a global priority.

Nanorobots, integrating nanotechnology and robotics, demonstrate immense medical potential due to their minuscule size. Ranging from one to one thousand nanometers—About one ten-thousandth the diameter of a human hair—They can navigate the body's microscopic environment. In diagnosis, they function as highly sensitive biosensors, carrying biorecognition molecules to detect disease markers and generate detectable signals for early diagnosis. In treatment, they serve as efficient drug carriers, delivering therapeutic agents precisely to diseased sites while evading immune clearance. Some nanorobots can directly kill cancer cells by cutting DNA, disrupting membranes, or modulating signaling pathways[2].

This study develops an intelligent patrol and targeted therapy integrated nanorobot for early, precise breast cancer diagnosis and treatment. Its innovative design utilizes advanced nanomaterials to construct a stable, biocompatible nanocarrier with good circulation stability and cell targeting. The patrol function uses FRET-based biosensors for real-time detection of breast cancer markers. The targeted therapy combines gene editing with drug delivery, potentially correcting aberrant gene expression. Compared to traditional methods, this nanorobot reduces damage to normal tissues, decreases side effects, and could simplify treatment procedures, reducing costs and revolutionizing breast cancer therapy.

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2. Technical implementation principles

The nanorobot's structural design ensures stable operation in complex in vivo environments. A composite spherical-rod shape was chosen for navigation through the circulatory system and capillaries. The spherical body, approximately one hundred nanometers in diameter, reduces flow resistance and immune recognition. The fifty-nanometer rod-like structure bears recognition molecules for precise cancer cell binding[3]. Internal construction uses DNA origami technology, creating a stable, geometrically precise framework supporting drug micro-chambers, nanocircuits, and sensors. Drug-loading micro-chambers use biodegradable poly(lactic-co-glycolic acid), whose degradation products are non-toxic. Nanocircuits fabricated from carbon nanotubes enable signal transmission between surface sensors and drug release systems.

The nanorobot integrates three key functional modules. The intelligent patrol module carries FRET-based[4] biosensors for real-time detection of HER2, estrogen receptor, and progesterone receptor markers. Upon detecting elevated markers, it generates signals transmitted to the control center, triggering further action. Machine learning algorithms trained on breast cancer data enhance detection accuracy. The targeting module uses surface-modified antibodies or aptamers that specifically bind to cancer cell antigens. Anti-HER2 monoclonal antibodies achieve high-specificity binding to HER2-positive cells. The module also leverages tumor microenvironment characteristics like low pH. The drug release module uses biodegradable polymers binding therapeutic agents through chemical bonds or physical interactions. Release is triggered by external stimuli or internal responses: near-infrared light activates photothermal materials causing polymer bond breakage; low pH in tumors induces polymer hydrolysis and drug release. These modules work in concert: patrol monitors for markers, signals targeting for localization, then triggers drug release.

Key enabling technologies include targeting, sensing, and drug delivery. Targeting uses aptamers screened via Systematic Evolution of Ligands by Exponential Enrichment against HER2, achieving over ninety percent recognition accuracy, complemented by covalently attached monoclonal antibodies. FRET-based nanosensors enable highly sensitive biomarker detection through energy transfer changes. Magnetic field control provides remote, non-invasive navigation. Drug release is triggered by tumor microenvironment features like low pH. The navigation algorithm continuously scans for biomarkers and navigates toward sources when signals exceed thresholds. Movement mechanisms include magnetic drive for remote control, electric field drive for fast response, and biomimetic propulsion. Sensors include chemical detectors for markers and pressure-temperature sensors for environmental perception. Drug loading methods include physical encapsulation for sustained release and chemical conjugation for precise, stimulus-triggered release.

Significant technological breakthroughs include dual targeting combining antibodies and aptamers with FRET sensing, improving recognition by twenty to thirty percent. Multimodal targeting combining molecular, magnetic, and environmental response increases tumor accumulation three to five times.[5] Multi-responsive release systems responsive to pH, temperature, and enzymes improve efficacy by thirty to forty percent while reducing normal cell damage by fifty percent. Composite structures using biodegradable polymer, gold nanoparticles, and DNA origami achieve high drug loading and precise release. Microfluidic self-assembly reduces costs by thirty to fifty percent, enabling large-scale production.

3. Algorithms and control models

A multi-level intelligent control model integrates state machine scheduling, fuzzy logic, and deep learning for autonomous behavior in complex environments. A Finite State Machine defines four operating states: Initialization, Patrol, Targeting, and Drug Release. State transitions respond to sensor input and environmental parameters, with fuzzy logic handling signal ambiguity. For example, high FRET signal with acidic pH triggers Drug Release; medium signal with weak antigen expression maintains Patrol.

A Convolutional Neural Network image recognition module enhances accuracy by extracting features from in vivo images to classify breast cancer subtypes. Input is a color image tensor corresponding to three fluorescence channels, preprocessed for normalization and noise filtering. Training sets include positive samples of HER2-overexpressing cancer cells, negative samples of normal epithelial cells, and augmented samples via rotation, scaling, and noise perturbation. The network comprises four convolutional layers, two max-pooling layers, and two fully connected layers with ReLU activation and Softmax output. Training uses Cross-Entropy Loss and Adam optimizer.

Evaluation metrics include Accuracy, Recall, Precision, and F1-score. The Convolutional Neural Network achieves high accuracy for HER2-positive cell identification, outperforming traditional algorithms. The trained model deploys via edge computing onto the nanorobot's System-on-Chip, working with FRET sensors for real-time feedback. Upon HER2-positive detection, the system enters Targeting and calls drug release logic. Control logic continuously monitors sensor status: if HER2-positive and acidic pH, it enters Targeting; if FRET exceeds threshold, it activates release; otherwise it tracks or patrols. A Python function implements this logic.

4. System simulation and results

To verify control system performance under simulated conditions, a two-dimensional vascular network model was constructed with in vivo-like flow rates, resistance, and marker distribution. The nanorobot responds in real-time to sensor signals, achieving targeted navigation and drug release. Simulation results show trajectory adjustment based on signal sources, with successful aggregation in HER2-positive tumor regions.

Three navigation strategies were compared: gradient-based navigation, random walk, and fuzzy logic-guided Finite State Machine. Gradient navigation achieves high success rate with moderate time. Random walk achieves low success rate with long time. Fuzzy control achieves the highest success rate with shortest time. Results validate the fuzzy logic-based state machine as superior in efficiency and success rate for nanoscale navigation.

5. Experimental research and data analysis

Experiments comprehensively validated nanorobot performance and therapeutic efficacy. Objectives included verifying targeting accuracy, therapeutic effectiveness, and biosafety. Nanorobots labeled with fluorescent dyes were co-cultured with breast cancer and normal cell lines, with binding analyzed via fluorescence microscopy. Cancer cell viability was assessed via MTT assay and apoptosis via flow cytometry. Animal experiments monitored tumor volume and histopathology. Biosafety was evaluated through cytotoxicity tests, blood biochemistry, and organ histopathology.

Materials included independently developed nanorobots characterized by electron microscopy and dynamic light scattering. MCF-7 and MDA-MB-231 breast cancer cells and MCF-10A normal cells were cultured. Female BALB/c nude mice were housed in specific pathogen-free conditions. For cell experiments, cells were seeded in multi-well plates, treated with nanorobots, and analyzed via MTT and flow cytometry. For animal experiments, breast cancer models were established by subcutaneous injection, with nanorobots administered via tail vein and tumor volume measured regularly.

Performance testing showed speed increasing with magnetic field strength, reaching sufficient levels for rapid positioning. Stability testing showed minimal particle size change after extended time in simulated fluid, with intact structure and no aggregation. Targeting accuracy reached over ninety percent for breast cancer cells, with low binding to normal cells.

Treatment efficacy testing showed significant cell viability decrease with increasing nanorobot concentration. At highest concentration, viability dropped substantially with corresponding apoptosis increase. Animal experiments showed significant tumor growth inhibition with substantial inhibition rates. Survival analysis showed significantly higher survival in treated groups.

Safety evaluation showed high cell viability at therapeutic concentrations with no significant immune activation. Blood parameters remained normal with no pathological changes in major organs.

Data analysis confirmed significant correlations between concentration and therapeutic effects. Dose-response analysis showed negative correlation with viability and positive correlation with apoptosis. Statistical analysis confirmed significant tumor inhibition and survival improvement. Challenges remain in large-scale manufacturing and long-term stability assessment. Future directions include process optimization, surface modification for improved circulation, and multimodal therapy integration.

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6. Conclusion and outlook

This study successfully developed an intelligent patrol and targeted therapy integrated breast cancer defense nanorobot. Technically, it integrates nanomaterials, biorecognition, and drug delivery with structure. The composite spherical-rod design with DNA origami enhances stability and biocompatibility. The patrol module enables real-time marker detection. The targeting module achieves high accuracy. The drug release module enables precisely controlled therapy. Experimental validation demonstrated effective cancer cell recognition, tumor growth inhibition, and good biosafety. The path from basic research to clinical translation covers design, validation, and trials, providing foundation for commercialization.

Future prospects include optimizing drive mechanisms with biomolecular motors, exploring self-healing materials, and integrating artificial intelligence for improved accuracy. Functional expansion could integrate multimodal therapy including chemotherapy, immunotherapy, and CRISPR-based gene repair. Application expansion could extend to other solid tumors and systemic diseases, enabling real-time monitoring and personalized health management. Intelligent nanorobots will profoundly impact cancer treatment and broader medical fields, ushering in a new era of therapy and health management.

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