Nanobiotechnology in Cancer Therapy: Targeted and Personalized Treatments

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Abstract

The field of nanobiotechnology is changing how cancer is treated by joining nanotechnology with biology to deliver treatments that target individuals. Combining various techniques makes it possible to accurately deliver medicines, fight many drugs growing resistant, enhance immunity and cut the overall harmful side effects for the patient. Targeted delivery of drugs is achieved with specialized nanoparticles, using either passive or active strategies known as liposomal doxorubicin and polymeric nanoparticles. Nano-biosensors are used to discover biomarkers and nanocarriers are developed to deliver CRISPR/Cas9 and siRNA for genetic editing in this area. Theranostic systems that diagnose and treat at the same time, together with lights-based therapies called photothermal and photodynamic, give patients effective and less invasive treatments. Spite such challenges as toxicity, policies and ethics, new technologies such as smart nanoparticles, artificial intelligence and sustainable nanotechnology, are bringing good progress to oncology and encouraging wider and more effective use of their applications. Nanobiotechnology is expected to help more precisely treat cancer and benefit patients worldwide.

Keywords: Nanobiotechnology, Targeted Drug Delivery, Precision Oncology, Theranostic systems, Photothermal, Photodynamic

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Introduction

Cancer is still one of the toughest problems facing modern medicine, due to its biology, complex nature and malignant cells' willingness to adapt. Although chemotherapy, radiation therapy and surgery are central to cancer treatment, they usually have many disadvantages (Chu et al., 2024). Such drugs have limited specificity which harms the body's healthy cells, can lead to resistance and so reduces treatment success and living standards for patients. Since cancer is being discovered in more people worldwide, new strategies that address these challenges are needed quickly (Jacquemin et al., 2022).

The field of nanobiotechnology now provides important new treatments for patients dealing with cancer. The field combines deep knowledge in nanotechnology and biology, using the special features of very small materials to work with living systems at their smallest parts (Chehelgerdi et al., 2023). Because of their strong features such as large surface-area, adjustable size and more reactions, these nanomaterials are suited for new cancer treatment methods. Precision and versatility, nanobiotechnology supports new targeted, individualized and gentler methods for treating cancer (Mosleh-Shirazi et al., 2022).

The treatment of cancer around the world underlines why new innovations are required. WHO data reports that cancer caused about 10 million deaths around the globe in 2020, placing it as the second most common cause of death (Cao et al., 2024). As a result of this high number, we need to explore new treatments that offer more than existing approaches. Increasing numbers of cancer cases are partly due to older people, changes in how we live and greater contact with carcinogens, calling for attention to effective and patient-friendly approaches (Denburg et al., 2019).

Nanobiotechnology is already making major changes to oncology by helping to resolve some of the main problems seen in regular treatments. Making use of nanotechnology makes it possible to administer medication to certain body parts, offering controlled drug discharge and lowering toxic effects or side effects. Besides, when these diagnostic and treatment functions are merged in a single platform,

known as theranostics, it provides a convenient way to care for cancer. This way, the results from treatments can be checked as they happen and diseases can be noticed earlier, guiding better and more flexible reactions (Patra et al., 2018).

By involving several areas of science, nanobiotechnology is a big step forward in the fight with cancer. Improving effectiveness, reducing negative effects and merging diagnostic tools with treatment make it vital to future oncological care. Accepting these developments, health professionals are overcoming the issues of traditional methods and giving millions of patients' new reasons to hope (Ma et al., 2024).

2. Targeted Drug Delivery Systems

Targeted drug delivery systems are among the biggest contributions of nanobiotechnology to treating cancer. Unlike regular chemotherapy that shares drugs all over the body, these systems permit more local use of drugs, cutting down on the risks and boosting treatment at the tumor site. Nanotechnology enables doctors to send medications right to cancerous tissues, sparing the healthy ones, so the treatment works well and causes less harm (Yao et al., 2020).

2.1 Precision Drug Delivery Mechanisms

Nanotechnology for drug delivery depends mainly on passive and active targeting principles. Essentially, passive targeting is due to the EPR effect which allows nanoparticles to collect more in tumors than in healthy tissue because tumor blood vessels are abnormal and lymphatic drainage is reduced. With blood vessels having holes of 100 to 800 nm, large nanoparticles are able to enter and build up in tumor areas. Furthermore, slow lymphatic drainage in tumors stops the removal of nanoparticles, keeping them longer and allowing them to do their therapeutic work. Using this technique is most successful for nanoparticles sized 10–200 nm, because they slide past the kidneys and properly enter the tumor cells.

Targeting drug delivery more precisely is possible by loading nanoparticles with molecules such as antibodies, peptides, aptamers or other tiny molecules that adhere to the overabundant receptors known to be on cancer cells. Example: Nanoparticles decorated with antibodies for HER2 receptors bind only to cancer cells that over express HER2 and boost how effective the therapy is with much less damage to other cells (Yoo et al., 2019). In the same pattern, folate-attached nanoparticle systems target the increased presence of folate receptors in cancer cells from ovarian and lung tissues. With ligands attached to them, nanoparticles target cells accurately, enhancing the ability to carry out receptor-mediated uptake into cells (Anarjan, 2019).

2.2 Nanocarriers: Enhancing Drug Delivery Efficiency

Targeted drug delivery systems greatly rely on the use of nanocarriers. For instance, liposomes, dendrimers, polymeric nanoparticles and micelles are valuable due to the unique drug-encapsulating and delivering properties they all have. Phospholipid bilayers form spherical liposomes that include hydrophilic drugs in their inner aqueous region and hydrophobic ones in the surrounding layer (Alshawwa et al., 2022). Because of their increased solubility, better stability and more consistent bioavailability, chemotherapeutic agents in liposomes are considered safe and effective for drug delivery. PEG modification keeps the liposomes from being taken up by the MPS for longer because it reduces opsonization (Lu et al., 2021).

The tree-like structure of dendrimers and the large number of functional groups on their surface give them an ability to load drugs and adjust their surface chemical properties. Being extremely small and carefully made, these carriers accurately deliver substances where needed for treatment. As an example, PAMAM dendrimers are frequently examined for carrying cancer drugs such as methotrexate and doxorubicin (Mittal et al., 2021).

Polymeric nanoparticles with polylactic acid (PLA) and poly (lactic-co-glycolic acid) (PLGA) as biodegradable polymers ensure that drugs are released in a controlled pattern. They secure the drugs from early degradation and give a structural base for attaching targeting agents to the nanoparticles' surface. Both the paclitaxel and EGFR-targeting peptide on PLGA nanoparticles have increased the effectiveness of lung cancer models (Bhardwaj & Jangde, 2023). Self-assembled micelles, created by amphiphilic block copolymers, include both a core for hiding insoluble drugs and a surrounding layer for greater stability and solubility in aqueous solutions (Attia et al., 2011). These systems strongly support delivering paclitaxel and docetaxel which are hydrophobic chemotherapeutics. Transferrin-functionalized micelles were found to deliver drugs right to glioblastoma cells because transferrin receptors are overexpressed in these tumors (Gaucher et al., 2005).

2.3 Integrated Treatment Approaches

Today, cancer treatment relies on combination therapy to increase the power of drugs and overcome ways cancer cells become resistant. Combination therapy includes several types of therapy, including chemotherapy, therapies based on RNA and those that alter the immune response, by administering all of them together in one treatment. The problems with pharmaceutical incompatibility, poor absorption rates and harmful side effects in typical combined therapies are minimized, leading to better therapeutic results (Mokhtari et al., 2017).

2.4 Combining Multiple Therapeutic Agents

Nanocarriers have the flexibility to deliver many kinds of therapeutic agents, mainly chemotherapeutics, small interfering RNAs and some immunomodulators. Treatments that target cancer cells when they divide such as chemotherapy can also include siRNA to shut off important genes that make cancer cells resistant to treatment. This combination helps make the treatment even more successful and counteracts reasons for failure (Subhan & Torchilin, 2019).

Doctors and scientists regularly depend on polymeric nanoparticles and liposomes for combination therapy. Using these nanocarriers, it

is possible to contain and deliver both hydrophilic and hydrophobic drugs in the simplest way. Tumor models that were resistant to treatment showed better results when liposomal systems were loaded with doxorubicin and siRNA targeting MDR1. The siRNA knockdown of the MDR1 gene restores sensitivity to doxorubicin in the tumor and helps slow down tumor growth.(Parveen et al., 2023).

Nanotechnology is being used more often to combine immunomodulators which strengthen the immune system, with standard cancer treatments. Nanoparticles with both chemotherapy and anti-PD-1 or anti-CTLA-4 antibodies act in two ways: they harm cancer cells and help the immune system attack cancer. Combing treatments improves how the immune system works and makes it less likely that cancer will come back (Thakur et al., 2020).

2.5 Boosted Effectiveness and Minimized Resistance

It is very useful that nanocarriers can give therapeutic agents at the same time in our bodies. Differences in how drugs are absorbed or eliminated sometimes cause one drug to be delivered at a different time than another in a traditional combination regimen, lowering the effects of the treatment. This problem is addressed by nanocarriers which carry and release numerous agents together at the tumor site (Din et al., 2017). In breast cancer models, the combination of paclitaxel and curcumin in PLGA nanoparticles produced stronger results than those substances used separately. Paclitaxel reduces the functioning of microtubules, while curcumin blocks the NF-κB way which is a factor in drug resistance. The combination treatments increase cancer cell death and at the same time reduce the risk of inflammation and boost the effectiveness of cancer treatments. Because of these systems, patients take lower doses of medications which lowers the chance of side effects in the body (Baek & Cho, 2017).

In addition, nanocarriers keep therapeutic drugs stable and prevent them from degrading too early. Since enzymes in the blood can quickly degrade RNA therapies, it is especially important for them. Wrapping siRNA into nanoparticles allows it to reach its target and become more effective in therapy. Polymeric nanoparticles containing both cisplatin and surviving-siRNA have helped control tumor growth in ovarian cancer studies. Dual-action nanoparticles show how combination therapy can produce the best possible therapeutic outcomes. These systems work on several cancer biology matters at the same time such as excessive growth, avoiding the immune system and resistance (Zare et al., 2022).

Using gold nanoparticles that absorb light in photothermal therapy (PTT) with chemotherapy is a new way to treat cancers. Activated by near-infrared light, these chemotherapy-carrying nanoparticles make heat around tumors which affects their blood vessels and increases the therapy's arrival to the tumor. Loading doxorubicin onto gold nanoparticles for PTT has led to tumor ablation that is more effective than the use of just one of these approaches (Han & Choi, 2021).

These systems are also used to deliver more than one drug at once. Building polymeric micelles using paclitaxel and bevacizumab has shown that the drug pair works best by addressing cancer growth and the formation of blood vessels. The combination interrupts blood delivery to tumors and encourages tumor cells to die, resulting in better outcomes in glioblastoma testing (Wang et al., 2010).

2.6 Tailored Therapeutic Approaches

Customized therapy for cancer is becoming a reality to considering each patient's personal genetic, molecular and clinical makeup and nanotechnology helps make this happen. Because cancer has many different genetic mutations and markers, doctors must use carefully designed treatments for each patient, especially since these factors differ within a single tumor. With nanotechnology, it is possible to tailor therapies by offering precise testing, directed drug transport and ways to alter DNA. Such nano-sensors are able to recognize particular cancer markers in the body with great accuracy and sensitivity, according to Alghamdi et al. (2022). With the use of sensors, scientists can identify molecules such as DNA, RNA or proteins that indicate cancer in the body which helps to manage both early detection and continual therapy tracking. Carbon nanotube sensors have recently been employed to discover KRAS mutations in colorectal cancer, directing personalized care and leading to improved results (Mikaeeli et al., 2024). Nanotechnology helps to specifically deliver CRISPR/Cas9 and siRNA, two gene-editing tools that are changing how we treat cancers caused by genetic mutations. These nanocarriers stop the medicines from breaking down during their time in the blood and direct them to the required cancerous cells. Lipid nanoparticles have shown to be very useful in getting CRISPR/Cas9 elements to oncogene mutations, both correcting genetic alterations and killing cancer cells. When loaded with siRNA, nanoparticles have been made to block the gene codifying for MDR1, making chemotherapies more effective against drug-resistant cancers. Using these nanocarriers, therapeutic agents go where they are needed most, protecting against wrong targets and harmful side effects (Zhou et al., 2024).

It also helps design a single platform called theranostics that can detect biomarkers and treat them at the same time. Imaging tumor-specific biomarkers, gold nanoparticles also allow chemotherapy or gene editing, so patients can move smoothly from being diagnosed to being treated (Raheem et al., 2023). Using multimodal machines simplifies care, boosts the success of treatments and reduces the number of invasive tests needed. Besides, being able to alter the environment surrounding a tumor is essential for personalized medicine. The use of nanoparticles in the tumor microenvironment changes the environment which can improve both the response to therapy and the activation of the immune system. Personalized nanomedicine has demonstrated the advantage of overcoming common problems with cancer treatment, making therapies both safer and more effective than one-size-fits-all options. Developments in nanotechnology will enable personalized cancer care and help narrow the gap between research and actual use at the patient's bedside (Al-Thani et al., 2024).

3. Development of Theranostic Platforms Combining Imaging and Treatment

The unique traits of nanomaterials, including how easy it is to adjust their size, their high surface area and how diverse their functions are, are used by theranostic platforms to bring together therapies and imaging tools. These platforms serve to give therapy as well as inform physicians about the tumor's location, size and reaction to the therapy. It is important for such work to support precision oncology which means treatments are changed in response to how the tumor behaves at every stage (Kim et al., 2024). Their multifunctionality and ability to

adapt make nanoparticles the main basis of theranostic platforms. Some research teams apply quantum dots for imaging, as well as delivering cancer drugs into the cancerous cells. In addition, polymeric nanoparticles can include substances useful for scanning (such as gadolinium for MRI) and also carry medicines designed to stop cancer growth (like doxorubicin). With these hybrid tools, clinicians can instantly see both the spread and the success of the given treatment within the body (Altinbasak et al., 2024).

Among important advances in theranostics, stimuli-responsive nanoparticles have been developed that release their medicines in reaction to changes in pH, temperature or enzymes. Because they work best only where the environment is acidic and holds enzymes, they are highly valuable in cancer therapy. At the same time, their imaging features let doctors track the therapy immediately, so they can tell right away if the treatment is having the desired results (AlSawaftah et al., 2022).

4. Real-Time Monitoring of Treatment Efficacy

Getting real-time updates on the safety of treatments is one of the greatest advantages of using theranostics. As a result, specialists can recognize how tumors react to treatment and can respond quickly by adjusting therapy, to help patients avoid unwanted side effects. For example, using gold nanoparticles in photothermal therapy helps doctors keep track of temperature in the tumor as treatment goes along, ensuring cancer cells are destroyed without hurting other tissues. Their optical imaging properties, specialized nanoparticles can be used to see a tumor shrink in real time, allowing for quick results (Lee et al., 2020). In a similar manner, using magnetic materials in MRI-theranostics lets clinical staff distribute medicine continually and monitor how the tumor responds. Adding therapeutic agents to tiny magnets helps doctors see how the medicine reaches the tumor and watch the results of the treatment. For patients with metastatic cancer needing to treat several tumors, this type of imaging is very helpful (Gauger et al., 2020).

One new area of theranostics is the use of nanoparticles with molecular probes to find drug resistance when it happens. These systems spot signs of resistance in the cancer, so doctors can treat the patient differently before the cancer grows. Just as an illustration, with HIFs, theranostic nanotechnology targets the regions in tumors where blood is deficient, while delivering and activating medicine that kills resistant cancer cells (Sun et al., 2023).

5. Light-Based Nanotechnology Therapies

Light-based nanotechnology methods are highly modern and are widely used for treating various cancers. Through these techniques, light is used to make nanoparticles or photosensitizers active in the tumor, so cancer cells are eliminated precisely without hurting neighboring healthy cells. By combining these therapies with immune therapy, their potential as therapies for cancer increases through a kind of teamwork (Overchuk et al., 2023).

6. Photothermal Therapy (PTT) with Gold Nanorods and Nano shells

Photothermal therapy relies on nanomaterials that change captured images of light into heat, killing cancer cells. Among all agents, gold nanorods and nano shells have an edge in PTT due to their excellent near-infrared (NIR) light absorption which makes it easiest for light to penetrate tissues. The gold-based nanoparticles, when activated by NIR light, cause the temperature of tumor cells to increase so much that they die. Heat triggers injury inside the cells and also harms the vessels supplying the cancer, making it grow more slowly (Riley & Day, 2017). The aspect ratio of gold nanorods is easy to adjust, making it possible to control how they interact with light. Gold nanorods have been shown in studies to cause hyperthermia in tumors and reduce tumor growth in test models. Similar to other gold structures, gold nano shells (a core with a gold coating) are used in the treatment of breast and prostate cancer with PTT. It has been proven in studies that nano shell mediation of PTT may support treatment either on its own or in cooperation with chemotherapy to help drugs reach the target by widening blood vessels (Yu et al., 2024). Using Nanoparticle Photosensitizers for Photodynamic Therapy (PDT) PDT depends on photosensitizers which, when exposed to light, generate ROS and harm both the cancer cells and the cells around them. Photosensitizers benefit from nanoparticle-based delivery, as it improves their stability, helps them reach the right tissue and enhances their usefulness because of the problems caused by their poor solubility and fast clearance by the body (Zhou et al., 2016).

Many clinicians rely on porphyrin-based photosensitizers in PDT. Their pharmacokinetics and tendency to build up in tumors are greatly enhanced when they are put in nanoparticles. In fact, using liposome-encapsulated porphyrins enhances the tumor-related production of ROS, helping ablate it more than applying normal free photosensitizers may. In addition, when silica nanoparticles are functionalized, they show high efficiency in treating breast cancer in animal models. By co-delivering photo-agents and other medicines, nanoparticles can produce better therapeutic effects. In the case of hybrid nanoparticles joining photosensitizers with chemotherapeutics, the effects on tumor growth are higher because many pathways involved in oxidative damage and apoptosis are activated (Akbar et al., 2023).

7. Synergy of Light-Based Therapies and Immune Activation

A major advantage of light-based nanotechnology therapies is their ability to trigger the immune response which opens the door for better cancer treatments. Immunogenic cell death (ICD) is triggered by each method, making TAAs and DAMPs available to boost response from the immune system against tumor cells. Along with the main cytotoxic effects of light, immune activation extends how long these therapies are effective and decreases the risk of tumor regrowth (Guo et al., 2022). As a result, PTT of tumors leads to TAAs and heat shock proteins which dendritic cells and other antigen-presenting cells detect, prompting the activity of cytotoxic T lymphocytes. Work with gold nanorods indicates that PTT helps more CD8+ T cells reach the tumor site, leading to better overall anti-tumor defenses. In the same way, PDT-triggered ROS led to cell destruction and also draw immune cells to where the tumor is located. Nanoparticle-enhanced PDT is able to present TAAs at a better level, encouraging strong T-cell immune responses. Moving on to first-generation treatments, joining PDT with immune checkpoint inhibitors like anti-PD-1 antibodies has led to long-lasting tumor regression in studies done with animals (Zhang et al., 2022).

8. Nanoparticles in Combatting Drug Resistance

Drug resistance is a major problem for cancer treatment, primarily for cancers that grow and return. Several things contribute to cancer MDR such as overactive efflux pumps, changes in drug targets, improved DNA repair and avoiding apoptosis. Because of these factors, chemotherapy drugs often do not work well which causes the disease to continue advancing and treatments to fail. Experts believe that nanotechnology is helping deal with drug resistance by allowing the use of targeted therapy, eliminating pathways that make drugs less effective and restoring the ability of medicines to work (Emran et al., 2022).

8.1 Targeted Delivery of Agents against Resistance Pathways

Nanoparticles help conveniently deliver small interfering RNA (siRNA) and CRISPR/Cas9 gene-editing systems to disregard pathways implicated in drug resistance. siRNA-loaded nanoparticles can efficiently block the MDR1 gene which codes for the P-gp pump and therefore stops the cells from developing drug resistance to therapy. By using lipid nanoparticles, scientists have shown that MDR1-targeted siRNA can restore paclitaxel's effects on ovarian cancer cells and lead to major tumor shrinkage in animal studies (Huang & Xiao, 2022). Using gene-editing tools inside nanocarriers gives a stronger method for handling resistance. CRISPR/Cas9 allows scientists to remove genes that make bacteria immune or repair changes in the genome that cause therapy unwanted side effects. Researchers have found that gold nanoparticles, designed for use with CRISPR/Cas9, disrupt the expression of P-gp proteins in breast cancer cells resistant to many drugs (Xu et al., 2021). Nanoparticles allow apoptosis factors to be sent to frog eggs, overcoming the resistance issue. Polymeric nanoparticles holding Bcl-2 inhibitors have been found to help overcome resistance to chemotherapy in cancer by stimulating apoptosis in cells with strong anti-apoptotic proteins (Yoo et al., 2024).

8.2 Restoring Treatment Sensitivity with Targeted Molecular Interventions

Treatment effectiveness in resistant tumors is improved when targeted drugs act on the nearby cell environment and its inner activity, made possible by nanotechnology. Often, the microenvironment of a tumor protects cancer cells from therapy by offering supportive zones through lack of oxygen, acidic surroundings and joint characteristics of non-cancer cells. Devices consisting of nanoparticles that only release their drug when the tissue has low pH or less oxygen ensure that resistant cancer cells receive the healing agents while healthy tissues are not damaged (Fernandes et al., 2018). In other words, nanoparticles may carry materials that modify cancer metabolism to help fight resistant cancer. Such carriers, when given loads of 2-deoxyglucose, can stop cancer cells from getting the necessary energy, improving the results of traditional therapies. Through focusing on the metabolic adaptations of resistant cells, nanoparticles weaken their ability to keep multiplying during treatment. A strategy that combines both types of drugs shows great promise. Cancer cells' resistance to chemotherapy can be overcome by nanoparticles containing both paclitaxel and HDAC inhibitors which act by changing the cell's epigenetic profile and restoring sensitivity. Targeting both genetic and epigenetic parts of resistance helps cover possible MDR in a single treatment (Wang et al., 2024).

Conclusion

The use of nano particles in cancer treatment helps focus therapy cuts side effects and raises the success rate. Even so, the full potential of nanomedicine in medical practice is kept limited by nanoparticle toxicity, unknown long-term outcomes, complex regulations and high manufacturing costs. Questions about how people should have access to their own treatments and how genetics should be used add more issues to this topic. Continuing with new ideas, advanced particles that react to various signals and using artificial intelligence may solve these issues. Also, greener and cost-effective manufacturing tries to make nanomedicine larger and more sustainable. Because of interdisciplinary efforts and conscious innovations, nanotechnology may make cancer care safer, more successful and accessible to all.

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