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Biomedical Applications of Nanotechnology in Oncology and Targeted Drug Delivery

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Description

The field of nanotechnology has revolutionized many disciplines, especially medicine, where it plays a pivotal role in oncology and targeted drug delivery. Nanotechnology enables precise treatment strategies by creating and manipulating materials at the nanoscale, offering an innovative approach to cancer therapy and drug delivery. The integration of nanotechnology into oncology has significantly improved therapeutic outcomes, minimized side effects and improved patient quality of life by delivering drugs specifically to cancer cells, sparing healthy tissues. Nanotechnology involves engineering materials at a scale of 1-100 nanometers, a size range that allows unique physical, chemical and biological interactions. These nanoparticles can interact with cells, DNA and proteins in ways that traditional therapies cannot, making them ideal for biomedical applications. In oncology, nanoparticles can be engineered to specifically target cancerous cells, deliver drugs and even perform imaging functions, making it possible to diagnose and treat cancer at an earlier stage. The design of nanoparticles for targeted drug delivery offers potential advantages over conventional chemotherapy. Traditional chemotherapy circulates throughout the body, impacting both cancerous and healthy cells, often resulting in adverse side effects. Nanoparticles, however, can be engineered to selectively target tumor cells, ensuring that the therapeutic agents are released only at the disease site. This specificity is achieved by functionalizing the nanoparticle surface with ligands, such as antibodies or peptides, that bind specifically to receptors expressed on cancer cells.

Drug delivery vehicles

Liposomes: These are spherical vesicles composed of lipid bilayers that can encapsulate both hydrophilic and hydrophobic drugs. Liposomes are among the first nanosystems approved for clinical use in drug delivery. They improve drug solubility, stability and therapeutic efficacy. In oncology, liposomal formulations such as Doxil, a liposomal version of doxorubicin, are used to treat ovarian cancer, breast cancer and Kaposi's sarcoma.

Polymeric nanoparticles: Made from biodegradable polymers like Polylactic Acid (PLA) and Polyglycolic Acid (PGA), these nano-particles offer controlled drug release and are suitable for delivering a wide range of anticancer drugs. The polymeric matrix allows for a sustained and controlled release of the drug over time, improving therapeutic outcomes and reducing side effects.

Gold nanoparticles: Gold Nanoparticles (AuNPs) exhibit unique optical properties that make them ideal for imaging and therapeutic purposes. They can be conjugated with drugs and targeting ligands and their ability to absorb light enables photothermal therapy, where light is converted to heat to kill cancer cells. AuNPs are particularly effective for treating superficial tumors and are being studied for their potential in breast cancer, prostate cancer and skin cancer therapies.

Dendrimers: These are highly branched, tree-like polymers with a well-defined structure, enabling high drug loading capacity and surface functionality. Dendrimers can carry both hydrophobic and hydrophilic drugs, as well as imaging agents, making them versatile for both therapy and diagnostics. They are being investigated for use in treating breast, lung and liver cancers.

Mechanisms of targeted drug delivery

Nanoparticles can be functionalized to achieve active or passive targeting. Passive targeting takes advantage of the Enhanced Permeability and Retention (EPR) effect, where nanoparticles accumulate in tumor tissues due to the leaky vasculature and poor lymphatic drainage characteristic of tumors. Active targeting involves modifying the nanoparticle surface with specific ligands that bind to cancer cell receptors. For instance, targeting HER2 receptors in breast cancer or folate receptors in ovarian cancer has shown great potential in improving treatment efficacy. One of the most potential applications of nanotechnology in oncology is theranostics a combination of therapy and diagnostics in a single platform. Nanoparticles designed for theranostics can diagnose, monitor and treat cancer simultaneously, offering a personalized treatment approach. Quantum dots and iron oxide nanoparticles, for instance, can be used for imaging while also delivering therapeutic agents. The ability to monitor treatment response in real time is an invaluable advantage in oncology, as it allows for adjustments in therapy based on the patient's response.

Quantum dots: QDs are semiconductor nanoparticles that emit fluorescence when exposed to light, making them ideal for imaging applications. When functionalized with targeting ligands and therapeutic agents, QDs can simultaneously deliver drugs to tumors and allow imaging to track drug distribution and efficacy.

Iron oxide nanoparticles: Iron oxide nanoparticles are often used as contrast agents in Magnetic Resonance Imaging (MRI) due to their magnetic properties. By conjugating them with anticancer drugs, they provide a dual function, allowing doctors to visualize tumors while delivering therapy. They have shown efficacy in detecting and treating cancers like brain, breast and prostate cancer.