Nanotechnology in Drug Delivery

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ABSTRACT

Nanotechnology uses super tiny materials—so small you can't see them even with a regular microscope—to help deliver medicines more effectively inside the body. These materials are called "nanoparticles," and they're usually between 1 to 100 nanometers in size. This technology helps overcome many problems of traditional drug delivery, like poor targeting and low absorption Nanoparticles are tiny particles, thousands of times smaller than a grain of sand, that can be used to carry medicines inside the body. They act like smart delivery trucks, protecting the drug from being destroyed too early and helping it reach exactly where it's needed, like a sick cell or organ. This makes treatments more effective, with fewer side effects, because the medicine doesn't spread all over the body. Nanoparticles can also help control how fast the drug is released, ensuring it works over a longer time. This technology is already helping in cancer treatments and is being explored for many other diseases. However, more research is needed to make sure these tiny carriers are safe and work as intend. [1]

Keyword : - *Nanoparticles, drug delivery, nanotechnology, adverse Drug Reaction .*

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1. Introduction

Nanotechnology for Drug Delivery:
1. Targeted Delivery:
Active targeting: Nanoparticles can be designed to find and stick to specific markers on diseased cells (like cancer), which helps avoid harming healthy cells.
Passive targeting: Because tumors have leaky blood vessels, nanoparticles can naturally gather more in these areas, making drug delivery more effective.[2]
2. Controlled Drug Release: Nanoparticles can be made to release the drug slowly or only in response to certain conditions (like changes in pH or temperature). This helps maintain the right drug level in the body and reduces side effects.
3. Better Absorption: Some drugs don't dissolve well in water, making them hard to absorb in the body. Nanoparticles can help improve their solubility and stability, making the treatment more effective.[3]

1.1 Applications in Cancer Treatment

Scientists have used nanoparticles to successfully deliver various anti-cancer drugs like paclitaxel, doxorubicin, 5-fluorouracil, and dexamethasone. They've also used materials like quantum dots, chitosan, and PLGA nanoparticles to deliver RNA-based therapies in lab studies. Treating brain cancer is especially hard because drugs have trouble crossing the blood-brain barrier—a protective layer around the brain. But certain nanoparticles carrying drugs like doxorubicin and loperamide have been able to cross this barrier and reach the brain in effective amounts. Researchers are also exploring nanomaterials that can target specific molecules involved in cancer, like VEGF (a protein that helps tumors grow blood vessels) and cell adhesion molecules (which help cancer cells stick and spread). This opens up new possibilities for stopping cancer from growing or spreading.[4]

1.2 Types of Nanocarriers (Tiny Drug Carriers):

1. Liposomes:

These are tiny bubble-like structures made from fats (phospholipids). They can carry both water-loving and fat-loving drugs, making them very versatile.
2. Polymeric Nanoparticles:
Made from safe, biodegradable materials like PLGA. They release drugs slowly over time, which helps keep the drug working longer.[5]
3. Dendrimers:
These are tree-like molecules with lots of branches. Their unique shape makes them good for attaching drugs in a precise way.
4. Solid Lipid Nanoparticles (SLNs):
These are made from solid fats and help keep drugs stable and release them in a controlled way.
5. Carbon Nanotubes & Quantum Dots:
These are still being studied because they may be toxic to the body. Scientists are figuring out how to make them safer.[6]

2. Application of Cancer Treatment:

- Nanocarriers help target tumors more accurately, which reduces damage to healthy cells.
- Brain Disorders: They can cross the blood-brain barrier more easily, getting medicine into the brain where it's needed.
- Infections: Nanocarriers can deliver antibiotics more effectively to fight harmful bacteria.
- Gene Therapy: They're used to safely carry genetic material like DNA, RNA, or CRISPR tools into cells to fix genetic problems.[6]
- Challenges in Using Nanoparticles for Drug Delivery: Although nanoparticles offer great promise for delivering drugs effectively, there are still some major challenges: They may cause long-term side effects or reactions in the body. Making them is complicated and often expensive.
- It's tough to get approval from regulatory agencies. Ensuring their stability and producing them on a large scale can be difficult. However, nanotechnology is gaining a lot of interest because it can help solve many problems related to drug and gene delivery.[7]

2.1 Designing Nanoparticles for Drug Delivery:

Nanoparticles can be designed to deliver drugs directly to the affected area in the body. This helps: Improve how well drugs are absorbed .Target drugs to specific locations. Increase drug effectiveness and reduce side effects. Some common drugs like paclitaxel, doxorubicin, and 5-fluorouracil have been successfully delivered using nanoparticles. Materials like PLGA and PLA are often used to make nanoparticles that carry drugs such as dexamethasone .Dexamethasone is a type of glucocorticoid, a drug that works inside cells. It's used in cancer treatment because it can slow down or stop cell growth and reduce inflammation. It works by entering cells and binding to receptors in the cytoplasm (the fluid inside cells). This drug-receptor pair then moves into the nucleus, where it turns on specific genes that help control how cells grow and divide.[8]
When dexamethasone is packaged in special nanoparticles—tiny carriers that release the drug slowly over time—it can completely stop the growth of certain cells, like vascular smooth muscle cells. These kinds of drug delivery systems, which include liposomes, micelles, and nanoparticles, are widely studied for cancer treatment. Their benefits come from being small in size, reducing side effects, releasing the drug steadily, and improving how the drug spreads through the body.[9]One of the major challenges in cancer treatment is drug resistance. Many cancer cells learn to defend themselves by producing a protein called P-glycoprotein. This protein can pump chemotherapy drugs out of the cell before they have a chance to work. However, nanoparticles might be able to sneak drugs into these resistant cells without triggering this pump .Researchers tested this idea using paclitaxel, a common chemotherapy drug. When paclitaxel was packed into nanoparticles and given to mice with drug-resistant colon cancer, it was able to get inside the cancer cells and work effectively. One challenge with paclitaxel is that it doesn't dissolve well in water, but scientists found that combining it with a natural protein called albumin helps. This version of the drug, called Abraxane, is already approved for use and comes as a nano-sized injectable suspension.[10]

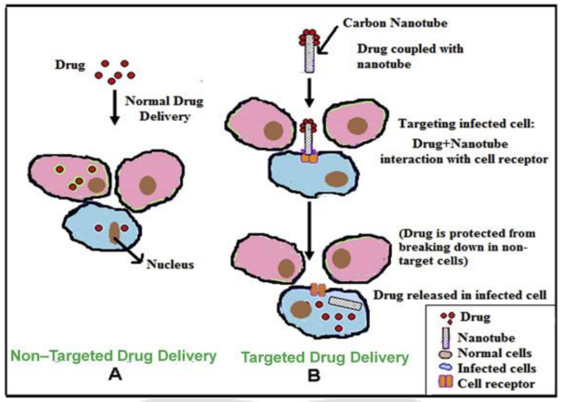

Fig -1 Designing Nanoparticles for Drug Delivery

Paclitaxel is a drug used to treat breast cancer, but in earlier versions, it had to be mixed with a substance called Cremophor-EL. This solvent often caused serious allergic reactions. To prevent this, patients had to take steroids and antihistamines before treatment and receive the drug slowly over a few hours. A newer version of paclitaxel, called Abraxane, is bound to a protein called albumin instead of using a solvent. This allows doctors to give higher doses of the drug in a shorter time and avoids the allergic reactions caused by Cremophor-EL. In a major clinical trial, Abraxane worked nearly twice as well as the older, solvent-based version (Taxol).[11]

2.2 Using Nanoparticles to Deliver siRNA

Small interfering RNA (siRNA) is a powerful tool for turning off specific genes, with many potential medical uses. But to make this type of treatment work in real patients, we need better ways to deliver siRNA into the body. Scientists have tried using different types of nanoparticles to do this. For example, quantum dots (tiny fluorescent particles) have been used to track where the siRNA goes.[12] Other nanoparticles made from materials like PLGA and PLA have been used to deliver siRNA in lab tests. However, one big challenge is knowing whether the siRNA has reached the right place and is working — without something that lets us see or track it, that's hard to do.To solve this, researchers have created a special type of nanoparticle made from chitosan (a natural material) and quantum dots. These particles can carry siRNA and glow, making it possible to track where they go. One study used these glowing nanoparticles to deliver siRNA that targets the HER2 gene, which is often overactive in certain breast cancer cells. By adding a HER2-specific antibody to the surface of the nanoparticles, they could deliver the treatment directly to cancer cells that have too much HER2.[13]

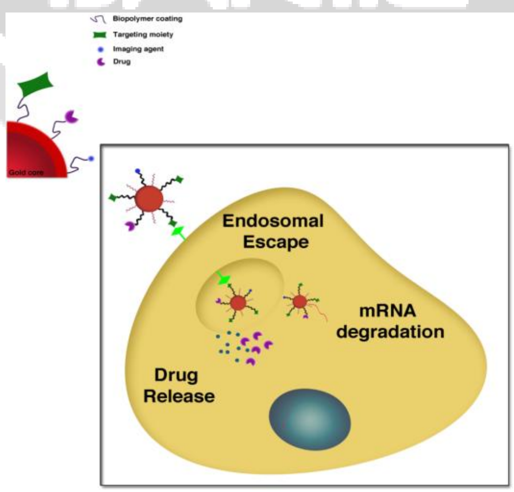

Fig 2- Using Nanoparticles to Deliver siRNA

2.3 Targeting Cancer with Nanoparticles:

Especially brain cancer, is hard to treat because drugs often can't cross the blood-brain barrier (a protective layer that prevents many substances from entering the brain). Scientists have found that nanoparticles can carry drugs across this barrier. For example, a painkiller called loperamide, which normally doesn't reach the brain, was attached to albumin nanoparticles and combined with apolipoprotein E, which helps the complex cross into the brain. In mice, this combination allowed the drug to work effectively. Researchers are also designing multi-functional nanoparticles like PEBBLEs, which can do several jobs at once: find tumors, help doctors see them using imaging, and deliver treatment—all in one tiny package. Another drug, doxorubicin, when attached to certain nanoparticles, can even cross into the brain and target tumors more effectively .Here's a more human-friendly version of the text: Nanoparticles for Brain Tumor Targeting Some specially designed tiny particles, called superparamagnetic iron oxide particles, can help find brain tumors earlier and more accurately than current methods. These particles can be modified with folic acid and polyethylene glycol, which improves their ability to reach and enter cancer cells. This makes them promising carriers for delivering cancer-fighting drugs directly to the brain, where they can pass through protective barriers and reach the tumor in effective doses.[14]

2.4 Method for Nanoparticles:

There are two main methods to create nanoparticles
1. Bottom-Up Approach: This method builds nanoparticles from the ground up — starting with atoms or molecules that come together to form structures. It can be done by:
Templating: Using materials like polymers or surfactants to guide the formation of particles.
Non-templating: Letting atoms or molecules self-assemble under certain conditions without a fixed template.This approach allows for more precise and creative designs, but it can be tricky because atoms move randomly and are hard to control.
2. Top-Down Approach: This involves breaking down larger materials into nanoscale particles. Techniques include:
Photolithography: Using light to etch patterns.
Electron beam and X-ray lithography: Using beams to carve out structures. These techniques are useful, but it's difficult to make particles smaller than 100 nanometers with them.[15]

3. Nanotechnology in Treating Inflammation

3.1 Targeting Macrophages to Fight Infections

Macrophages are immune cells that recognize and destroy harmful substances in the body .Because of this, scientists are exploring ways to specifically target macrophages with nanoparticles to help control inflammation in various diseases. However, some microbes (like Toxoplasma, Leishmania, Tuberculosis, and Listeria) have developed ways to survive inside macrophages.[16] They do this by hijacking the cell's systems and living in modified compartments inside the cell. To counter this, nanoparticles can be used to deliver antimicrobial drugs directly into these infected compartments within the macrophages. This targeted approach can help eliminate hidden infections more effectively and with fewer side effects. For example, PACA (poly alkyl cyanoacrylate) nanoparticles have been successfully used to deliver drugs to fight Leishmania infections in macrophages without triggering harmful inflammation. Systems like these could be very useful in treating chronic infections where these immune cells are involved.[17]

3.2 Targeting Inflammatory Molecules with Nanotechnology

In the last 20 years, scientists have discovered many important molecules called cell adhesion molecules that help cells stick to each other and move through tissues. These molecules are found on the surface of cells and play a key role in guiding immune cells like neutrophils and monocytes to areas of inflammation or infection. They are grouped into four main types: integrins, cadherins, selectins, and the immunoglobulin superfamily. While these molecules are essential for fighting infections, too many neutrophils in inflamed organs—like the lungs—can cause serious tissue damage. Because of this, researchers are working on ways to better control the movement of these immune cells to reduce harmful inflammation. Thanks to advances in our understanding of these molecules, new drugs—such as small proteins and peptides—are being developed to treat diseases like cancer, heart disease, and autoimmune disorders (like type 1 diabetes).One example involves RGD peptides, which can target specific types of integrins (avβ3 and avβ5) found on tumor blood vessels. These peptides have been attached to cancer drugs like paclitaxel and doxorubicin to make them better at finding and attacking tumor cells. In studies with mice that had human breast cancer, those treated with a doxorubicin-RGD.[18] compound (Dox-RGD4C) survived, while untreated mice did not—showing how effective targeted therapy can be. Researchers are also studying how these targeted systems affect immune responses, such as signaling through pathways like P38 kinases and how they influence neutrophil behavior in humans, cows, and horses. Another promising molecule is the CLABL peptide, which can bind to ICAM-1, a molecule that becomes more active during inflammation and cancer. Scientists attached this peptide to methotrexate (MTX)—a drug that reduces inflammation and is used to treat cancer and autoimmune diseases. The resulting compound, MTX-CLABL, can deliver the drug more directly to inflamed or cancerous tissue. Interestingly, MTX-CLABL works a bit differently than regular methotrexate: it's better at reducing levels of the inflammation-causing molecule IL-6, while methotrexate alone is more effective against IL-8. This suggests that the modified version could be used more precisely depending on the type of inflammation.[19]

3.3 Benefits of Nanotechnology

Nanotechnology offers many advantages around the world, helping both developed and developing countries in various ways:

- New and Better Products: It helps create entirely new products and improve the ones we already use.
- Stronger Materials: It makes construction materials that are stronger, lighter, and more durable—great for building and engineering projects.
- Clean Drinking Water: Nanotech-based filters can remove harmful germs and toxins, making water safer to drink.
- Environmental Cleanup: It can help clean up pollution by removing harmful substances from soil, air, and water.
- Better Healthcare: Tiny devices and smart drug delivery systems allow for earlier disease detection, better treatment, and more effective management of chronic illnesses.
- Smarter Transportation: It leads to better vehicle designs, improved fuel efficiency, and safer travel.
- Affordable Clean Energy: Nanotechnology helps create cleaner and cheaper sources of energy, like solar panels and better batteries.

In short, nanotechnology combines knowledge from many fields and is driving a new industrial revolution that could improve almost every part of our lives.[20]

3.4 Risks of Nanotechnology

Even though nanotechnology has huge potential, there are still concerns about its safety for humans, animals, plants, and the environment .One major worry is its possible use in the military—especially in creating new chemical weapons. Because nanoparticles are so small, they can have a much stronger effect, which could make them more dangerous than current weapons. Some nanoparticles can be toxic. For example, studies show that carbon nanotubes can harm lung cells and cause serious reactions in lab animals. Other tiny particles made from metals like copper, cobalt, titanium oxide, and silicon oxide have been shown to cause inflammation and damage to cells. Scientists are still researching the full effects of nanotechnology. There's ongoing debate about how to balance its powerful benefits with potential risks. The good news is that most experts believe the benefits can outweigh the risks—as long as we continue studying the health, safety, environmental, and ethical issues involved. Just like with earlier technologies, we need to manage the risks carefully while using the technology to improve lives.[21]

4. CONCLUSIONS

This review looked at recent progress in using advanced materials and nanotechnology for delivering drugs across the body's natural barriers. Two main technologies were discussed: microneedle arrays (for delivering drugs through the skin) and nanoneedle arrays (for delivering drugs directly into cells).Microneedle arrays are showing great promise, especially for treating skin diseases, giving vaccines, and delivering medicines in a painless and simple way. They are less risky than regular needles, don't need special storage or trained professionals, and are easier to use—making them ideal for use in a variety of settings, even without advanced medical infrastructure. The same concept is now being applied inside the body using nanoneedles, aiming for efficient, safe, and high-throughput drug delivery directly into cells. While microneedle technology is already in clinical trials and closer to real-world use, nanoneedles are still in the early stages of development. More research is needed to prove their benefits and fine-tune how they're made and used. In summary, this research highlights the exciting advances in drug delivery using microneedle and nanoneedle technologies. It encourages more scientists to explore new solutions through materials science and nanotechnology, and to conduct lab studies and clinical trials that will move these innovations closer to everyday medical use.[22]

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