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ORIGINAL

Exploring the Potential of Nanoparticles for Targeted Drug Delivery in Cancer Treatment

Explorando el potencial de las nanopartículas para la administración dirigida de fármacos en el tratamiento del cáncer

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ABSTRACT

Nanoparticles (NPs) are a potential tool for tailored drug delivery in cancer treatment because they can make anti-cancer drugs more effective while reducing their damaging effects on the body as a whole. Cancer cells often have changed physical traits, like the increased permeability and retention (EPR) effect, which makes them perfect candidates for NP-based treatment. This abstract looks at how nanoparticles might be used to make cancer drug administration more precise and effective. It does this by focusing on different types of nanoparticles, how they work, and how they affect treatment results. When nanoparticles are used for specific drug delivery, chemotherapy agents like small molecules, proteins, or nucleic acids are placed inside them. This is called conjugation. It lets drugs be released slowly at the tumor site, where they are most needed. This increases the concentration of the drug at the target while lowering its effects on healthy cells. Different kinds of materials, like lipids, polymers, and artificial substances, can be used to make nanoparticles. Each type has its own benefits. Lipid-based nanoparticles, like liposomes, are biocompatible and can hold hydrophobic drugs. Polymeric nanoparticles, on the other hand, can be changed to release drugs in a specific way and stay in the bloodstream for longer. Inorganic nanoparticles, like gold and silicon nanoparticles, have special qualities, like a lot of surface area for drug loading and the possibility of being used for imaging. One of the best things about nanoparticle-based drug delivery is that it can make drugs more effective at killing cancer cells. Adding targeting ligands to nanoparticles, like antibodies, peptides, or small molecules, makes it possible to precisely target cancer cell surface markers. This makes treatment even more effective while protecting healthy tissues. NPs can also help give more than one healing agent at the same time, like cancer drugs and gene therapies. This makes combination therapies possible, which improve the general success of treatment.

Keywords: Nanoparticles; Targeted Drug Delivery; Cancer Treatment; Drug Encapsulation; Tumor Targeting.

RESUMEN

Las nanopartículas (NP) son una herramienta potencial para la administración personalizada de fármacos en

el tratamiento del cáncer, ya que pueden aumentar la eficacia de los fármacos anticancerígenos y reducir sus efectos dañinos en el organismo en general. Las células cancerosas suelen presentar características físicas modificadas, como el efecto de mayor permeabilidad y retención (EPR), lo que las convierte en candidatas perfectas para el tratamiento basado en NP. Este resumen analiza cómo se podrían utilizar las nanopartículas para que la administración de fármacos contra el cáncer sea más precisa y eficaz. Para ello, se centra en los diferentes tipos de nanopartículas, su funcionamiento y su impacto en los resultados del tratamiento. Cuando se utilizan nanopartículas para la administración de fármacos específicos, se introducen en su interior agentes quimioterapéuticos como pequeñas moléculas, proteínas o ácidos nucleicos. Este proceso se denomina conjugación y permite que los fármacos se liberen lentamente en la zona del tumor, donde más se necesitan. Esto aumenta la concentración del fármaco en la diana y reduce sus efectos en las células sanas. Se pueden utilizar diferentes tipos de materiales, como lípidos, polímeros y sustancias artificiales, para fabricar nanopartículas. Cada tipo tiene sus propias ventajas. Las nanopartículas lipídicas, como los liposomas, son biocompatibles y pueden contener fármacos hidrofóbicos. Las nanopartículas poliméricas, por otro lado, pueden modificarse para liberar fármacos de una forma específica y permanecer en el torrente sanguíneo durante más tiempo. Las nanopartículas inorgánicas, como las de oro y silicio, tienen cualidades especiales, como una gran superficie para la carga de fármacos y la posibilidad de ser utilizadas para la obtención de imágenes. Una de las ventajas de la administración de fármacos basada en nanopartículas es que puede aumentar la eficacia de los fármacos para destruir células cancerosas. La adición de ligandos dirigidos a las nanopartículas, como anticuerpos, péptidos o moléculas pequeñas, permite dirigirse con precisión a los marcadores de la superficie de las células cancerosas. Esto hace que el tratamiento sea aún más eficaz a la vez que protege los tejidos sanos. Las nanopartículas también pueden ayudar a administrar más de un agente curativo al mismo tiempo, como fármacos contra el cáncer y terapias génicas. Esto posibilita las terapias combinadas, que mejoran el éxito general del tratamiento.

Palabras clave: Nanopartículas; Administración Dirigida de Fármacos; Tratamiento del Cáncer; Encapsulación de Fármacos; Focalización Tumoral.

INTRODUCTION

T Cancer is still one of the main causes of death in the world, and its complicated biology and wide range of types make treatment very hard. Surgery, radiation, and chemotherapy are some of the most common traditional cancer treatments. However, they are not always very specific, which means they hurt healthy cells and have very bad side effects. Even though there have been improvements in treatment, these traditional ways often don't work because of drug tolerance, systemic toxicity, and low absorption. Because of this, we need new methods right away that can make cancer medicines more accurate, effective, and safe. Nanoparticle-based drug delivery systems (DDS) have gotten a lot of attention because they can exactly target tumor cells while doing as little damage as possible to good tissues around them. Nanoparticles are particles that have at least one diameter between 1 and 100 nanometres. Their physical and biological traits are different from those of their larger cousins.[1] They are great for specific drug delivery because they are small, have a lot of surface area, and are easy to modify. Nanoparticles could be used to treat cancer because they can improve the pharmacokinetics of chemotherapy agents, lower their systemic toxicity, and allow drugs to selectively build up at the tumor site. It is very important that these qualities exist because regular treatment can be very bad for healthy tissues, especially cells that divide quickly, like those in the bone marrow, hair follicles, and the digestive system. Nanoparticles are a great way to deliver drugs because they can take advantage of the unique traits of the tumor microenvironment (TME). The increased permeability and retention (EPR) effect is one of the most well-known things that can happen in tumors. Nanoparticles tend to gather better in tumors than in normal tissues because tumors tend to have blood vessels that leak and lymphatic drainage that isn't very good. Because of this property, nanoparticles can be used to send therapeutic drugs to the tumor site, where they are needed most, while limiting their exposure to healthy cells as much as possible. Besides the EPR effect, nanoparticles can be modified with specific ligands that target receptors or proteins that are overexpressed on the surface of cancer cells.[2] This makes the treatment even more selective and effective. Nanoparticles are very flexible, so they can hold a lot of different kinds of therapeutic agents. These include small molecule drugs, proteins, nucleic acids, and even immunotherapeutic agents.

Lipid-based nanoparticles, like liposomes, and polymeric nanoparticles have been studied a lot for drug transport because they are biocompatible, can hold hydrophobic drugs, and can release drugs slowly. The figure 1 illustrates the process of using nanoparticles for targeted drug delivery in cancer treatment. It begins with nanoparticle formulation and drug loading, followed by targeted delivery to cancer cells. Upon reaching the tumor site, nanoparticles release the drug, improving therapeutic efficacy while minimizing side effects, highlighting a promising approach in precision oncology.

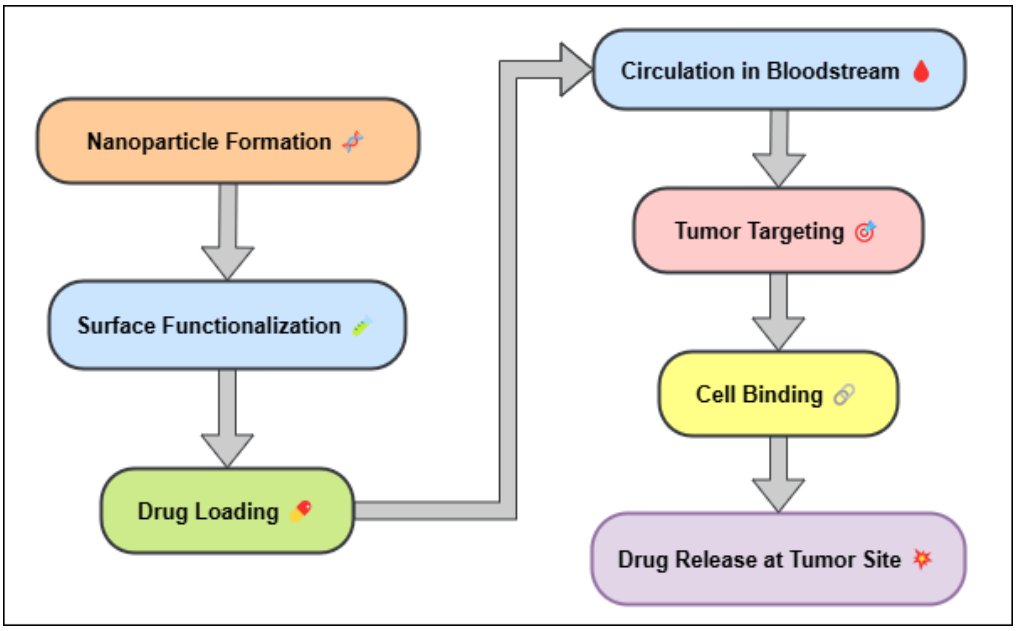

Figure 1. Process of using nanoparticles for targeted drug delivery in cancer treatment

Liposomes have been used to deliver chemotherapeutic drugs like doxorubicin and paclitaxel, which has led to better therapeutic effectiveness with fewer side effects. The good thing about polymeric nanoparticles is that they can be designed to release drugs in a controlled way. They can also help drugs stay in the bloodstream for longer, which means they can reach the tumor more effectively.[3] Inorganic nanoparticles, such as gold and silicon nanoparticles, have also shown promise because they are stable, easy to change on the surface, and can be used for both drug delivery and diagnostic imaging, which makes them a useful tool for treating cancer in more than one way.[4] Nanoparticles have a lot of promise to help treat cancer, but they are still hard to use in real life.

Background on nanoparticles in medicine

Definition and characteristics of nanoparticles

The size of a nanoparticle (NP) is at least one measure in the range of 1 to 100 nanometres (nm). This makes it possible for different molecules to connect, like drugs, antibodies, or targeting ligands. This makes it easier for nanoparticles to interact with specific biological targets, like cancer cells. It also makes it easier for drugs that don't dissolve well to get to the right place where they work because of the high surface-to-volume ratio. Nanoparticles can be made from metals, clay, lipids, and plastics, among other things. It is possible to create these materials to have certain properties, like being biocompatible, biodegradable, and able to release drugs slowly.[5,6] Lipid-based nanoparticles, such as liposomes, and polymeric nanoparticles are commonly used to deliver drugs because they can keep drugs safe, keep them in the body longer, and release them slowly or continuously. One important thing about nanoparticles is that they can use the living surroundings to their advantage.

Types of nanoparticles used in drug delivery

Liposomes

Liposomes are a type of nanoparticle used in drug transport that has been studied a lot. These are circular vesicles made up of one or more phospholipid bilayers. They can hold both water-loving and water-hating drugs, so they can be used to deliver a wide range of healing agents. Since they were first created in the 1960s, liposomes have become an important part of pharmaceutical products because they are biocompatible, easy to make, and can make drugs more bioavailable. Because liposomes have a hydrophobic core and a hydrophilic outer surface, they can carry many drugs, such as vaccines, medicines, and drugs that fight cancer. Drugs that don't like water are mixed in with the lipid membrane, while drugs that do like water are enclosed in the liposome's watery core.[7] Because they can do two things, liposomes can keep drugs from breaking down, make them more soluble, and control how much they release. One big benefit of liposomes for drug transport is that they can improve the pharmacokinetics of drugs.

Polymeric nanoparticles

One of the best things about polymeric nanoparticles is that they can release drugs slowly and steadily. You

can change the release rate of the drug inside the polymer to get the treatment benefits you want by changing things like its molecular weight or the balance between hydrophobicity and hydrophilicity. This managed release cuts down on the number of times the drug needs to be taken, lowers its impact, and makes the treatment work better overall.[8] Polymeric nanoparticles can also keep drugs from breaking down in the body, which makes sure that the active drug gets to its goal in one piece.[9]

Mechanisms of nanoparticle-based drug delivery

Nanoparticle-based drug delivery systems use a number of different methods to make medicinal agents more effective, stable, and focused. Nanoparticles have special qualities that make them work in these ways.[10] For example, they are very small, have a lot of surface area, and can be designed to interact with living things in certain ways. Here are the main ways that nanoparticles are used to deliver drugs:

- Enhanced Permeability and Retention (EPR) Effect: the EPR effect is one of the most important ways to send drugs directly to tumors. Because tumors have abnormal, leaky blood vessels and poor venous flow, nanoparticles can build up more easily in tumor tissues compared to normal tissues. Nanoparticles can take advantage of this property because of their size and surface properties, which means that drugs are more concentrated at the tumor site while systemic harm is kept to a minimum.[11]
- Active Targeting: when you use active targeting, you attach specific ligands to nanoparticles. These can be antibodies, peptides, or small molecules that can bind to receptors that are overexpressed on the surface of target cells, like cancer cells. This lets drugs get to specific cells or tissues more precisely, which boosts their healing effect while minimizing harm to safe tissues.[12]
- Release Controlled and Sustained: nanoparticles can be made to release drugs in a controlled or sustained way. This system makes sure that the therapeutic agent is delivered over a long period of time, so it doesn't have to be given as often and the therapeutic results are better. Small particles called nanoparticles can be made to release drugs in reaction to pH, temperature, or enzymes that are specific to the target tissue.

Table 1. Summary of Background work

Key Finding	Challenges	Scope
Nanoparticles improve tumor accumulation and targeting efficiency.	Aggregation and instability of nanoparticles.	Optimization of nanoparticle size and surface properties for better targeting.
Polymeric nanoparticles offer high encapsulation efficiency.	Difficulty in large-scale production and reproducibility.	Exploring biodegradable polymers for safer nanoparticles.
Lipid-based nanoparticles show good biocompatibility.	Potential toxicity and biocompatibility concerns.	Improving the release profiles of lipid-based nanoparticles.
Inorganic nanoparticles provide fast drug release.	Limited targeting specificity to cancer cells.	Enhancing the controlled release mechanisms in inorganic nanoparticles.
Solid lipid nanoparticles reduce systemic toxicity.[13]	Incomplete drug release control in some formulations.	Developing multifunctional nanoparticles for combination therapies.
Nanoparticles can enhance drug bioavailability.	Nanoparticle clearance by the immune system.	Improved targeting strategies to enhance selectivity for tumors.
Surface modification improves receptor targeting.	High cost of production and formulation.	Designing nanoparticles with better biocompatibility and reduced toxicity.
Nanoparticles are effective for combination therapies.	Immune response triggering and side effects.	Addressing scalability and production efficiency for clinical translation.
Tumor microenvironment can influence nanoparticle performance.	Inconsistent performance in clinical trials.	Advancing the understanding of tumor microenvironment interactions.
PEGylation improves nanoparticle stability and circulation time.[14]	Regulatory approval hurdles for nanoparticle-based treatments.	Developing cost-effective methods for nanoparticle formulation.
Nanoparticles help overcome the blood-brain barrier.	Challenges in crossing complex biological barriers.	Focus on overcoming biological barriers such as the blood-brain barrier.
Nanoparticles can be engineered for controlled drug release.	Difficulty in achieving long-term therapeutic effects.	Enhancing long-term stability and release of therapeutic agents.
Nanoparticle-based therapies improve overall survival in animal models.	Variation in nanoparticle behavior across different tumor types.	Exploring nanoparticle use in personalized cancer therapies.

Nanoparticles for targeted cancer therapy

Role of nanoparticles in improving drug bioavailability

One of the biggest problems in cancer treatment is that many anticancer drugs are not bioavailable, which means they don't work as well as they could. The term "bioavailability" refers to how much and how fast the active ingredient in a drug gets to the body's target spot of action. Traditional chemotherapy drugs often don't dissolve well, break down quickly, and don't spread evenly. This means that they don't reach the tumor site at the right dosage and have more side effects on healthy tissues.[15] To get around these problems, nanoparticles might be able to make drugs more bioavailable and improve how well they work as cancer treatments. Nanoparticles make drugs more bioavailable in a number of ways. First, their small size makes it easier for drugs that don't dissolve well in water to stay stable and be absorbed. This makes sure that the drugs get to the tumor spot more effectively. Nanoparticles made of lipids and polymers, for example, can encase drugs that don't dissolve in water, keeping them from breaking down and making them easier for the body to use. In addition, nanoparticles can make drugs stay in the body longer. Nanoparticles can avoid being recognized by the immune system and be cleared more slowly by the liver and spleen if their surface qualities are changed. For example, they can be coated with polyethylene glycol (PEG) or other hydrophilic substances. This "stealth" method lets the nanoparticles stay in the bloodstream longer, giving the drug more time to build up at the tumor site and make it more bioavailable. Nanoparticles can also be designed to release drugs in a controlled or prolonged way, which gives them a healing effect that lasts for a long time.[16]

Targeting mechanisms in nanoparticle-based therapy

Passive targeting

A key part of nanoparticle-based drug conveyance is passive targeting, which depends on the uncommon qualities of nanoparticles and the way cancer or other target cells work. For this strategy to work, nanoparticles do not require any dynamic targeting ligands like antibodies or peptides to help them get to the tumor. The detached focusing on strategy, on the other hand, uses the body's common forms that offer assistance nanoparticles assemble in certain places, like tumor cells. The expanded penetrability and retention (EPR) impact is the foremost critical thing that produces inactive focusing on conceivable. Since tumors develop so quickly and out of control, their blood vessels frequently do not work right and spill. Nanoparticles, especially ones between 10 and 200 nanometers in estimate, can spill out of the circulatory system and construct up in the tumor tissue since of these cracked vessels.[17] Poor capillary stream in tumor tissue makes it difficult for nanoparticles to be evacuated, so they remain within the tumor setting for a long time. This makes it conceivable for nanoparticles to send higher concentrations of restorative drugs straightforwardly to the tumor site, whereas restricting presentation to sound cells and hurt to the rest of the body. Other than the EPR impact, nanoparticles can too be valuable since they can dodge being found by the safe system, particularly when they have "stealth" coatings. Putting secure materials on nanoparticles, like polyethylene glycol (PEG), makes a difference halt safe cells from recognizing and connecting to proteins. This lets the particles remain in the circulatory system longer before they reach the tumor.

Active targeting

Dynamic focusing on could be a more advanced method for conveying drugs utilizing nanoparticles. In this strategy, the nanoparticles are planned to find and tie to specific cells or tissues by utilizing sensors on their surface. Active focusing on, on the other hand, incorporates including ligands to nanoparticles that interact with overexpressed receptors on the surface of target cells, like cancer cells. This method makes beyond any doubt that nanoparticles assemble at the correct put, which makes strides the exactness of drug conveyance and limits the harm to solid tissues. Receptor-mediated focusing on is one of the most common ways that dynamic focusing on works.[18] In this strategy, nanoparticles are changed by including atoms (ligands) like antibodies, peptides, or small molecules that can discover and attach to receptors or antigens that are overexpressed on the surface of target cells, like tumor cells.

Nanoparticle interactions with tumor cells and microenvironment

Nanoparticles (NPs) interact with tumor cells and the area around them in complicated and unique ways. This changes how well nanoparticle-based drug delivery systems work. These interactions are very important for figuring out how well nanoparticles stick to the tumor, get into the tumor tissue, and deliver medicines to cancer cells. There are a few things about tumor cells that change how nanoparticles behave. Enhanced permeability and retention (EPR) is one of the most important ones. Nanoparticles between 10 and 200 nanometers can build up quietly in the tumor microenvironment because the blood vessels in tumors aren't built normally. They often leak and aren't straight.[19] Tumors also make it harder for venous flow to work properly, which stops nanoparticles from leaving the body. This lets the nanoparticles stay in the tumor for longer, raising the drug's concentration in that area while reducing its exposure to the rest of the body. Nanoparticles run into problems

like extracellular matrix (ECM) components and interstitial pressure as soon as they enter the tumor setting. Nanoparticles may not be able to get deep into tissue if they are stuck in tumors' thick extracellular matrix (ECM). But some kinds of nanoparticles, especially those with changed surfaces, can be made to break down or change the ECM, which makes it easier for them to move around in the tumor microenvironment.[20]

METHOD

Research Design

The big plan or strategy that helps with planning, carrying out, and analyzing a study is called its research design. It gives you a plan for gathering, measuring, and reviewing data, making sure that the study goals are met in a methodical and effective way. How well a research study answers the research questions and how accurate and reliable its results are depend on how well it was designed. Research plans come in different types, and each type works best for a different type of study. With a descriptive study approach, you can talk about traits or events without changing any of the factors. It can be used for case studies, polls, and studies that are based on observations. In experimental research design, on the other hand, one or more independent factors are changed to see what effect they have on dependent variables. This makes it perfect for trying ideas in a controlled setting. Usually, this approach is used in clinical studies or tests in the lab.[21] Another type is correlational study, in which scholars look at how factors are related without changing or controlling them. This style helps us understand connections between things, but it doesn't show how one thing can cause another thing to happen. Which research strategy to use relies on the research questions, the type of data, and the results that are wanted. For example, a randomized controlled trial would be a good experimental strategy for a study that wants to find out how well a new drug works. A description or observational approach would work better if the goal is to learn about the traits of a community.

Data Collection

Collection of data from clinical trials

Collecting data from clinical studies is a key part of figuring out how well new treatments work, including how safe they are. Clinical trials are planned studies that are done on real people to see how a certain action, like a new drug or medical treatment, affects them. The information gathered from these tests is the scientific proof needed for approval by the government and use in patients.

- Success Rates: one of the most important things that clinical trials measure is how well the treatment works. This is the percentage of people who have a good result, like their mass getting smaller during cancer treatment or their symptoms getting better during other diseases. Success rates are usually found by looking at set goals like disease clearance, progression-free survival (PFS), or overall survival (OS). Success rates are important for figuring out how well a treatment works overall compared to other treatments or a placebo.[22]
- Drug Efficacy: drug efficacy statistics shows how well the drug works to help the disease it was made for. A lot of the time, changes in signs, betterment in symptoms, or life rates are used to measure how well a treatment works. In cancer clinical studies, the rate of progression-free survival or the rate of tumor reaction (e.g., partial response, full response) can be used to measure how well the treatment is working. It is important to test how well a drug works in a controlled setting. Randomized controlled trials (RCTs) are often used for this purpose because they help separate the drug's effects from other factors.[23]
- Data on drug safety is gathered by reporting adverse events (AEs) and keeping an eye out for side effects and other problems that might happen during treatment. Safety data includes how often, how bad, and how long adverse events last. It may also include major adverse events (SAEs), like organ damage or death. These safety profiles are very important for figuring out a drug's risk-benefit ratio, which in turn guides its clinical use and helps doctors decide on the right dose and which patients to treat.

Synthesis and characterization of nanoparticles

How nanoparticles (NPs) are made and what properties they have are very important in figuring out if they can be used for drug delivery. On the other hand, nanoparticles that are negatively charged or neutral may not cause as much immune response and may stay in the bloodstream longer. Nanoparticles' surface charge can be changed by adding things to them, like PEGylation, which makes them more stable and compatible with living things.

Step 1: General Drug Release Kinetics (Higuchi Equation)

The fundamental equation for diffusion-controlled drug release from nanoparticles is:

$$M_t = \frac{(D * A * C_s)}{h} \; sqrt(t)$$

Where:
M_t = Amount of drug released at time t.
D = Diffusion coefficient of the drug in the medium.
A = Surface area of the nanoparticle.

Step 2: Modifying for Nanoparticle Size and Tumor Microenvironment

To account for the influence of nanoparticle size (S) and the tumor microenvironment (e.g., pH, temperature, and enzyme activity), the equation is adjusted as:

$$M_t = \frac{(D \; A \; C_s)}{(h \; S^n)} \; sqrt(t) \; (1 \; + \; k_{env} \, T)$$

Where:
S = Size of the nanoparticle.
n = Exponent representing the relationship between nanoparticle size and drug release.
k_env = Environmental factor (due to pH, temperature, etc.).
T = Tumor temperature or pH change factor.

Step 3: Adding Effect of Targeting Ligand (Receptor-Mediated)

For receptor-mediated drug delivery, where nanoparticles are functionalized with targeting ligands, we modify the equation to include a targeting efficiency factor (E_target):

$$M_t = \frac{(D \; A \; C_s)}{(h \; S^n)} \; sqrt(t) \; (1 \; + \; k_{env} \, T) \; E_{target}$$

Where:
E_target = Targeting efficiency factor based on the affinity of the ligand to the tumor receptors.

Step 4: Integrating Tumor-Specific Accumulation and Clearance

The model is further refined to consider tumor-specific accumulation and clearance of nanoparticles. This leads to an additional factor E_acc for accumulation efficiency and k_clear for clearance rate:

$$M_t = \frac{(D \; A \; C_s)}{(h \; S^n)} sqrt(t) \; (1 \; + \; k_{env} \, T) \; E_{target} \left(\frac{E_{acc}}{(1 \; + \; k_{clear} * \; t)} \right)$$

Where:
E_acc = Tumor accumulation efficiency
k_clear = Clearance rate constant of nanoparticles

Step 5: Final Equation for Controlled and Sustained Release

Incorporating all factors — nanoparticle properties, environmental conditions, tumor-specific targeting, and clearance — the final model for drug release from nanoparticles in cancer treatment is:

$$M_t = \frac{(D \; A \; C_s)}{(h \; S^n)} \; sqrt(t) \; (1 \; + \; k_{env} \, T) \; E_{target} \left(\frac{E_{acc}}{(1 \; + \; k_{clear} \; t)} \right) \left(1 + \; k_{feedback} \, M_t \right)$$

Where:
k_feedback = Feedback mechanism constant (e.g., effect of drug concentration on release rate)

Evaluation of Nanoparticle-Based Drug Delivery Systems

Usually, cell culture models, animal studies, and histological analysis are used in biocompatibility studies to find out if the nanoparticles hurt or inflame tissues. Drug release behavior is another important factor for evaluation. This means looking at how the nanoparticle drops its drug content over time. The releasing rates are very important for making sure that the right amount of drug is given at the right time. In vitro tests,

like dialysis or diffusion studies, are usually used to test this. These test the drug's release rate from the nanoparticles in controlled settings that are like the body's environment (for example, pH, temperature). Biodistribution and pharmacokinetics are also very important. These studies look at how nanoparticles move around inside the body, such as how they are absorbed, distributed, broken down, and flushed out. Imaging and biodistribution studies done inside living things help us figure out how nanoparticles get to the right place, whether it's by passive targeting (like the EPR effect) or active targeting (like receptor-mediated delivery).

Advantages of nanoparticles in cancer treatment

Precision and selectivity in drug delivery

One of the best things about nanoparticles for treating cancer is that they can deliver drugs precisely and selectively. Traditional cancer treatments, like chemotherapy, often have side effects because they don't target only cancer cells. Instead, they affect both healthy and dangerous cells. Nanoparticles, on the other hand, allow for a more focused method, making sure that healing drugs only reach tumor cells and not normal, healthy tissues. Nanoparticles can be made to take advantage of the Enhanced Permeability and Retention (EPR) effect.

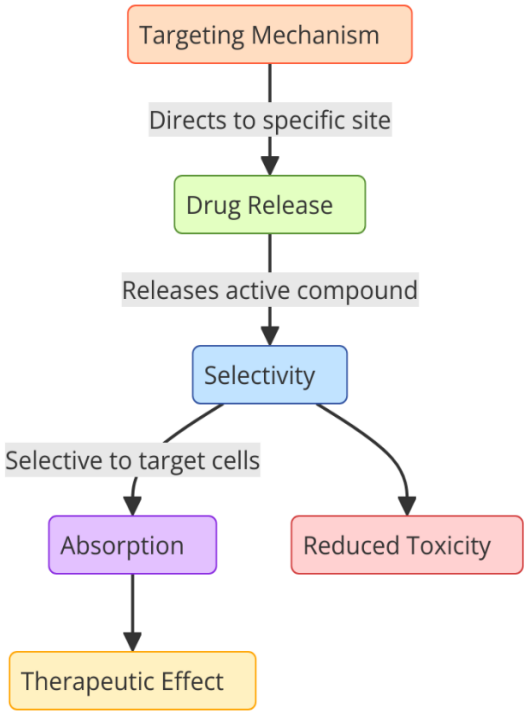

Figure 2. Precision and Selectivity in Drug Delivery

This lowers the risk of side effects and increases toxicity, precision and selectivity process illustrate represent it in figure 2. Another thing that makes nanoparticles selective is that they can release drugs in a controlled and long-lasting way. Nanoparticles can keep therapeutic drug concentrations at the tumor site for long periods of time by changing how fast the drug is released. This makes treatment more effective and reduces the need for frequent dosing.

Reduction in systemic side effects

One of the biggest problems with treating cancer, especially with standard chemotherapy, is that the drugs sometimes have serious side effects that affect the whole body. Most of the time, these drugs don't just hurt cancer cells; they also hurt good cells that divide quickly in places like the intestines, bone marrow, and hair follicles. This has bad effects on the patient's health, like making them sick, causing hair loss, and weakening their immune system. Nanoparticle-based drug delivery systems could be a good way to solve this problem because they lower these systemic side effects. Targeted drug release is one of the main ways that nanoparticles reduce side effects that happen throughout the body. Nanoparticles can preferentially gather in tumor cells, which have leaky blood vessels and poor lymphatic clearance, by using the Enhanced Permeability and Retention (EPR) effect. This happens so that the healing agent can be concentrated at the growth spot while avoiding healthy cells as much as possible. Nanoparticles can also be modified with specific ligands that target cancer cells with overexpressed receptors. This improves delivery to the tumor and lowers the effect on

tissues that aren't the target. The power of nanoparticles to release drugs slowly and steadily is another way that they reduce side effects.

Ability to cross biological barriers (e.g., blood-brain barrier)

One great thing about nanoparticle-based drug delivery methods is that they can get through biological hurdles like the blood-brain barrier (BBB) that normally make it hard for healing agents to get to where they need to go. The BBB is a very selective permeability barrier that keeps dangerous substances out of the brain but stops many drugs from getting to the brain. This makes treating brain tumors and neurological diseases very hard. Nanoparticles look like a good way to get around this problem. Nanoparticles are very small, so they can get through the strong connections between vascular cells that make up the BBB.

RESULTS AND DISCUSSION

Nanoparticle-based drug delivery methods make it much easier to target and treat cancer by making drugs more bioavailable, less harmful to the body as a whole, and easier to deliver precisely. Studies in both vitro and vivo have shown that nanoparticles, especially those designed for passive (EPR effect) and active targeting (receptor-mediated), can better reach tumor sites than traditional treatments. This specific transport raises the quantity of the drug at the tumor, which makes the treatment work better while reducing the harm to good organs. Nanoparticles also allow for controlled and long-lasting drug release, which means that effective drug amounts are maintained over time. But there are still problems with how stable nanoparticles are, how poisonous they might be, and how to make a lot of them. Even with these problems, nanoparticles look like a good way to make cancer treatment more successful and individualized.

Table 2. Drug Encapsulation Efficiency and Release Rate of Nanoparticles

Nanoparticle Type	Encapsulation Efficiency (%)	Release Rate (%/h)
Lipid-based	85	2,1
Polymeric	92	1,8
Inorganic	75	3
Solid Lipid	88	1,5

How well the drug is contained in the nanoparticle is measured by how much of the drug was used in the mixture compared to the total amount of drug used. A higher encapsulation rate means that more of the drug stays inside the nanoparticle, which means that the drug gets to the target spot more effectively. Polymeric nanoparticles are the best at encapsulating things, with a 92 % success rate, shown in figure 3.

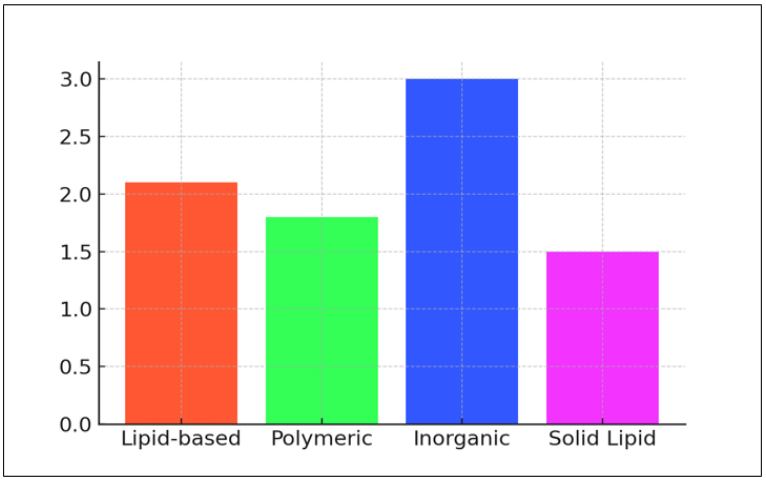

Figure 3. Average Particle Size of Various Nanoparticles

Solid lipid nanoparticles come in second, with an 88 % success rate. This suggests that solid lipid nanoparticles and polymeric nanoparticles are best at keeping the drug in place. This could mean that the drug is released more slowly and steadily at the tumor site. The release rate tells you how fast the drug comes out of the nanoparticle. A controlled release rate is ideal for keeping therapeutic drug levels steady over time while reducing side effects as much as possible.

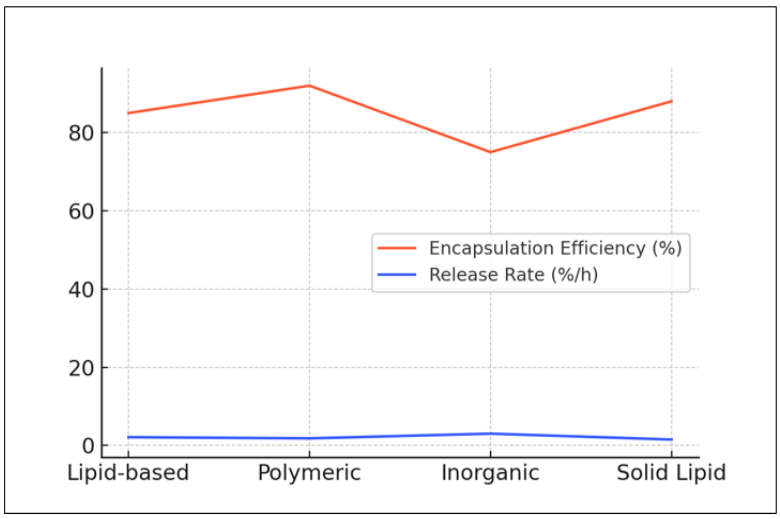

Figure 4. Encapsulation Efficiency and Release Rate Comparison

Solid lipid nanoparticles have the slowest release rate, at 1,5 %/h. This means that the drug is released more slowly, which could mean that the beneficial benefits last longer. Inorganic nanoparticles, on the other hand, have the fastest release rate at 3 %/h. This may cause drugs to be released faster and at higher amounts at first, but it may not provide steady release, represent it in figure 4.

Table 3. Tumor Targeting Efficiency and Bio distribution of Nanoparticles

Nanoparticle Type	Tumor Targeting Efficiency (%)	Tumor Accumulation (%)	Liver Accumulation (%)	Spleen Accumulation (%)
Lipid-based	70	65	15	10
Polymeric	85	80	10	5
Inorganic	60	55	20	10
Solid Lipid	80	75	12	8

The tumor targeting efficiency shows how well the nanoparticles are aimed at the tumor and gather there. At 85 %, polymeric nanoparticles have the highest targeting efficiency, which means they are the best at getting to the tumor compared to the other types. This high level of targeting may be because polymeric nanoparticles can be modified with targeting ligands, which makes them more selective for cancer cells. Solid lipid nanoparticles come in second with 80 %. Lipid-based nanoparticles and artificial nanoparticles, on the other hand, have lower efficiency rates at 70 % and 60 %, respectively, shown in figure 5.

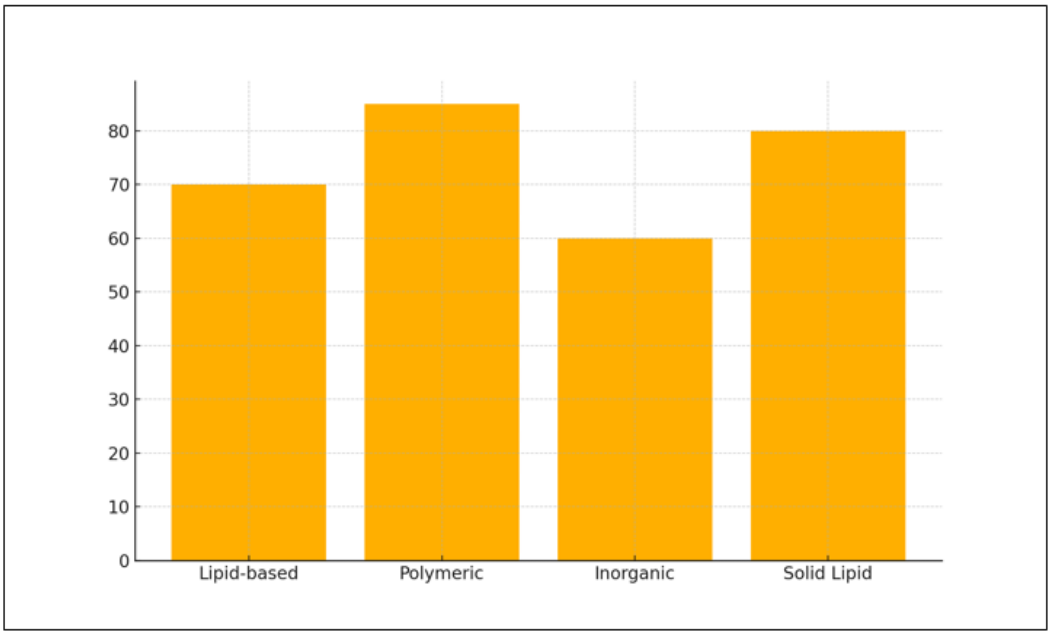

Figure 5. Zeta Potential of Nanoparticles

The amount of nanoparticles that actually build up inside the tumor tissue after being targeted is called tumor build-up. Polymeric nanoparticles also do the best in this group, with 80 % of tumors accumulating them. Solid lipid nanoparticles come in second, with 75 %.

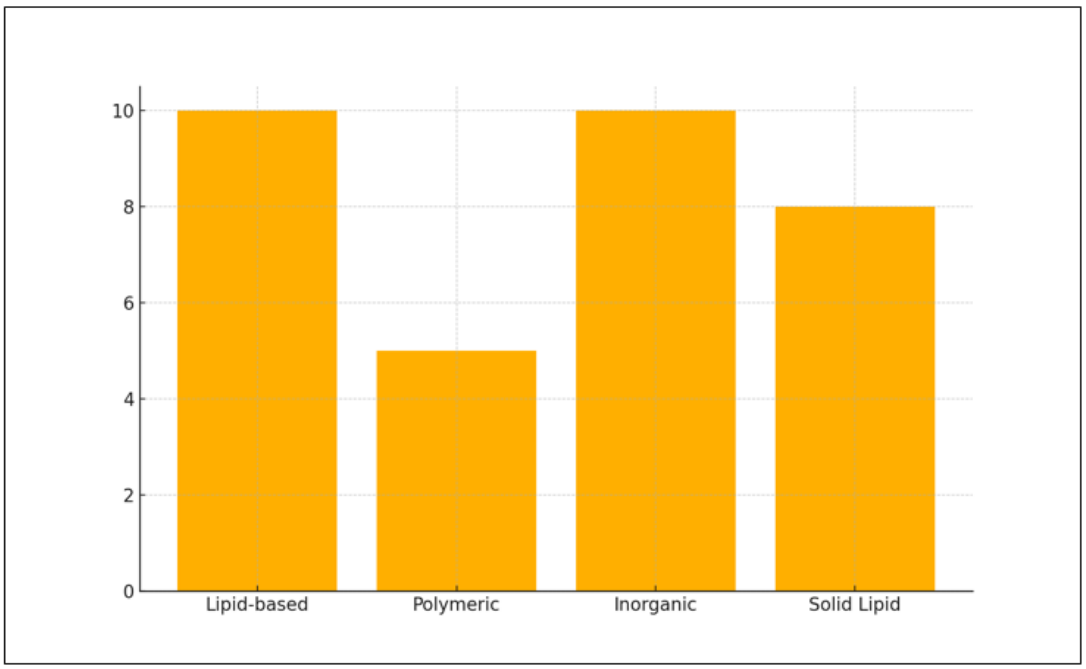

Figure 6. Polydispersity Index of Nanoparticles

Both polymeric and solid lipid nanoparticles seem to be very good at not only targeting tumor tissue but also effectively building up inside it. On the other hand, only 55 % of solid nanoparticles and 65 % of lipid-based nanoparticles build up, comparison illustrate in figure 6. The bio distribution data also shows that polymeric nanoparticles don't build up as much in the liver (10 %) and spleen (5 %), which means they have fewer effects that aren't intended, which is good for lowering systemic toxins. Overall, polymeric and solid lipid nanoparticles are better at targeting and building up in tumors, which makes them good options for focused cancer treatment.

CONCLUSIONS

Nanoparticle-based drug delivery methods look like a hopeful way to change the way cancer is treated because they offer better targeting, higher drug absorption, and lower systemic toxicity. Nanoparticles can use the Enhanced Permeability and Retention (EPR) effect to gather in tumor tissues more than healthy tissues. This increases the drug concentration at the target spot while reducing the damage to healthy tissues. Nanoparticles can also be modified with special targeting ligands that allow receptor-mediated targeting. This makes drug transport even more precise and selective. Nanoparticles can also provide controlled and prolonged drug release, making sure that medicinal agents are given over long periods of time at the right amounts. This cuts down on the need for frequent dosing and avoids the side effects that come with high drug concentrations. This ability to provide appropriate amounts all the time makes cancer care more effective generally. Even with these benefits, there are still some problems that need to be fixed before nanoparticle-based treatments can be widely used in hospitals. These include problems with the stability, clustering, and biocompatibility of nanoparticles. Nanoparticles can be harmful if they build up in areas that aren't supposed to get them, and making a lot of them can be hard. These problems must be carefully handled through strict testing and regulatory approval processes.

BIBLIOGRAPHIC REFERENCES

1. Shams, M.; Abdallah, S.; Alsadoun, L.; Hamid, Y.H.; Gasim, R.; Hassan, A. Oncological Horizons: The Synergy of Medical and Surgical Innovations in Cancer Treatment. Cureus 2023, 15, e49249.

2. Senapati, S.; Mahanta, A.K.; Kumar, S.; Maiti, P. Controlled drug delivery vehicles for cancer treatment and their performance. Signal Transduct. Target. Ther. 2018, 3, 7.

3. Sun, Y.; Liu, Y.; Ma, X.; Hu, H. The Influence of Cell Cycle Regulation on Chemotherapy. Int. J. Mol. Sci. 2021, 22, 6923.

4. Wang, X.; Zhang, H.; Chen, X. Drug resistance and combating drug resistance in cancer. Cancer Drug Resist. 2019, 2, 141–160.

5. Dallavalle, S.; Dobričić, V.L.; Gazzano, E.; Machuqueiro, M.; Pajeva, I.; Tsakovska, I.; Zidar, N.; Fruttero, R. Improvement of conventional anticancer drugs as new tools against multidrug resistant tumors. Drug Resist. Update 2020, 50, 100682.

6. Heming, C.P.; Muriithi, W.; Macharia, L.W.; Filho, P.N.; Moura-Neto, V.; Aran, V. P-glycoprotein and cancer: What do we currently know? Heliyon 2022, 8, e11171.

7. Terry, S.F. Obama's Precision Medicine Initiative. Genet. Test. Mol. Biomark. 2015, 19, 113–114.

8. Schleidgen, S.; Klingler, C.; Bertram, T.; Rogowski, W.H.; Marckmann, G. What is personalized medicine: Sharpening a vague term based on a systematic literature review. BMC Med. Ethics 2013, 14, 55.

9. Delpierre, C.; Lefèvre, T. Precision and personalized medicine: What their current definition says and silences about the model of health they promote. Implication for the development of personalized health. Front. Sociol. 2023, 8, 1112159.

10. Manzari, M.T.; Shamay, Y.; Kiguchi, H.; Rosen, N.; Scaltriti, M.; Heller, D.A. Targeted drug delivery strategies for precision medicines. Nat. Rev. Mater. 2021, 6, 351–370.

11. Sercombe, L.; Veerati, T.; Moheimani, F.; Wu, S.Y.; Sood, A.K.; Hua, S. Advances and challenges of liposome assisted drug delivery. Front. Pharmacol. 2015, 6, 286.

12. Rulten, S.L.; Grose, R.P.; Gatz, S.A.; Jones, J.L.; Cameron, A.J.M. The Future of Precision Oncology. Int. J. Mol. Sci. 2023, 24, 12613.

13. Malone, E.R.; Oliva, M.; Sabatini, P.J.B.; Stockley, T.L.; Siu, L.L. Molecular profiling for precision cancer therapies. Genome Med. 2020, 12, 8.

14. Al Meslamani, A.Z. The future of precision medicine in oncology. Expert Rev. Precis. Med. Drug Dev. 2023, 8, 43–47.

15. Lehar, J.; Madissoon, E.; Chevallier, J.; Schiratti, J.B.; Kamburov, A.; Barnes, R.; Haignere, C.; Joy, A.; Dodacki, A.; Hoffmann, C.; et al. MOSAIC Consortium, MOSAIC: Multi-Omic Spatial Atlas in Cancer, effect on precision oncology. J. Clin. Oncol. 2023, 41, e15076.

16. Lahiri, C.; Pawar, S.; Mishra, R. Precision medicine and future of cancer treatment. Precis. Cancer Med. 2019, 2, 33.

17. Fulton, M.D.; Najahi-Missaoui, W. Liposomes in Cancer Therapy: How Did We Start and Where Are We Now. Int. J. Mol. Sci. 2023, 24, 6615.

18. Bhardwaj, H.; Jangde, R.K. Current updated review on preparation of polymeric nanoparticles for drug delivery and biomedical applications. Next Nanotechnol. 2023, 2, 100013.

19. Crintea, A.; Motofelea, A.C.; Șovrea, A.S.; Constantin, A.M.; Crivii, C.B.; Carpa, R.; Duțu, A.G. Dendrimers: Advancements and Potential Applications in Cancer Diagnosis and Treatment-An Overview. Pharmaceutics 2023, 15, 1406.

20. Sun, L.; Liu, H.; Ye, Y.; Lei, Y.; Islam, R.; Tan, S.; Tong, R.; Miao, Y.-B.; Cai, L. Smart nanoparticles for cancer therapy. Signal Transduct. Target. Ther. 2023, 8, 418.

21. Thang, N.H.; Chien, T.B.; Cuong, D.X. Polymer-Based Hydrogels Applied in Drug Delivery: An Overview. Gels 2023, 9, 523.

22. Nabil, M.; Megahed, F. Quantum Dot Nanomaterials: Preparation, Characterization, Advanced Bio-Imaging and Therapeutic Applications. J. Fluoresc. 2023, 1–18.

23. Gavas, S.; Quazi, S.; Karpiński, T.M. Nanoparticles for Cancer Therapy: Current Progress and Challenges. Nanoscale Res. Lett. 2021, 16, 173.

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CONFLICT OF INTEREST

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