Nanoparticles for Cancer Therapy: A Revolution in Precision Oncology

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Abstract- **Cancer continues to be one of the leading causes of morbidity and mortality worldwide, owing to its complicated pathophysiology and limits in standard therapies such as chemotherapy, radiation, and immunotherapy. These old techniques frequently have limitations, including as cytotoxicity, lack of selectivity, and the formation of multidrug resistance. The development of nanotechnology has resulted in a paradigm change in cancer diagnosis and therapy. Nanoparticles (1-100 nm) have improved permeability and retention, lower toxicity, higher stability, biocompatibility, and precision targeting, making them a suitable vehicle for drug delivery and imaging applications. They address traditional treatment difficulties by increasing drug solubility, enabling tailored therapy, and boosting immune response modulation. This review investigates the role of several nanoparticles liposomes, polymeric nanoparticles, dendrimers, quantum dots, and silica nanoparticles in cancer therapy. In addition, it discusses their mechanics, therapeutic applications, and ongoing advances in nanoparticle-based therapy. While nanoparticles have enormous potential for personalized medicine and better therapeutic outcomes, their environmental and societal effects must be carefully evaluated as these technologies get closer to clinical implementation.**

Keywords- **Cancer, Chemotherapy, Nanoparticles, Cellular Targeting, Multidrug Resistance, Drug Delivery.**

I. INTRODUCTION

Uncontrolled, unpredictable cell division and invasiveness are characteristics of a group of disorders collectively referred to as cancer. The discovery of different cancer risk factors has been the subject of considerable research over an abundance of years. The genesis of certain malignancies has been strongly linked to particular environmental (acquired) variables, like pollution and radiation. However, determining cancer risk is significantly impacted by bad lifestyle choices such as smoking, stress, a poor diet, tobacco use, and inactivity. Although these extrinsic factors have been identified as major causes of cancer, it has proven difficult to determine the role of proto-oncogene mutations, tumor suppressor gene expression patterns, and DNA repair genes. Inherited genetics are only relevant in 5–10% of cancer cases. A further significant risk factor for cancer and many different types of cancer is growing older.[1]

Cancer is the second most significant cause of death globally and one of the major public health issues. An estimated 20 million additional cases are expected to occur by the end of 2024, according to the American Cancer Society. Surgery, chemotherapy, radiation therapy, targeted therapy, immunotherapy, and hormone therapy are among the traditional therapeutic modalities used to treat cancer.[2] Despite having the capacity for cytostasis and cytotoxicity, radiation therapy and chemotherapy are frequently linked with severe side effects and a high chance of recurrence.[3] The most common adverse effects include fatigue, gastrointestinal and skin diseases, neuropathies, bone marrow suppression, and hair loss. In addition, there are a few adverse effects that are unique to certain drugs, like bleomycin-induced cardiotoxicity and pulmonary toxicity and anthracyclines.[4] Precision therapy has grown since the introduction of targeted therapy. But there are still a lot of unwanted side effects, like multi-drug resistance, which reduces the effectiveness of treatment. Immunotherapeutic drugs have shown encouraging outcomes in treating primary cancer while also reducing the risk of recurrence and preventing metastatic cancer from spreading. However, one of the main adverse effects of immunotherapy is autoimmune illness.[5] Furthermore, research and fragments of evidence indicate that immunotherapy works better against lymphoma than solid tumors. The extracellular matrix (ECM) produced by these tumors is unique and makes it difficult for immune

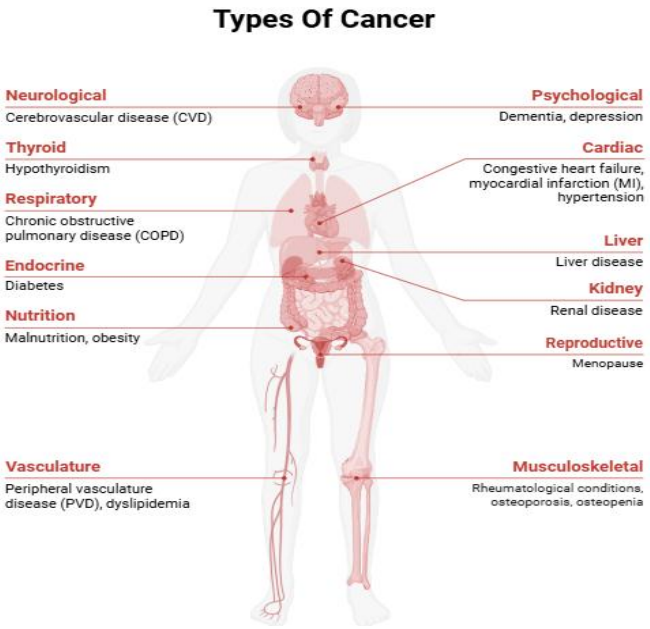
cells to penetrate. Dermatological adverse events (dAEs) are caused by these recently developed targeted medicines and immunotherapies that disrupt signaling pathways essential to malignant behaviors and normal homeostatic activities of the epidermis and dermis. Given all of these facts, there has been a recent surge in demand for the development of innovative approaches to find precise cancer treatment. Recent attempts have been made to use nanoparticles to overcome the shortcomings of current medicinal techniques.[6],[7] Drug delivery systems based on nanoparticles have shown promise in the treatment and management of cancer by exhibiting improved pharmacokinetics, accurate targeting, decreased adverse effects, and decreased drug resistance.[8]

Many nanotherapeutic medications have been commercialized and are currently being marketed extensively, and Since 2024, substantial advances in nanoparticle-based cancer treatments have arisen, bringing new promise for more precise and effective therapy. Researchers have created nanoparticles that increase drug delivery, enhancing chemotherapy efficacy while reducing side effects. One intriguing option is nanoparticle-directed photothermal therapy, which specifically targets cancer cells, particularly those in prostate cancer, and has shown good tumor reduction outcomes. Nanoparticles are also being used with immunotherapies to improve the immune system's ability to combat cancer. Nanoparticles are also utilized in photodynamic treatment, where they assist activate light-sensitive medicines that kill cancer cells. Ongoing clinical trials and studies demonstrate that nanoparticles can better target tumors, enhance medication solubility, and diminish resistance, ushering in an exciting new era of cancer treatment.[9],[10]

Types of Cancer

Almost every region of the body can acquire cancer. Typically, the types are classified according to the tissue or organ from which they are derived. The following are a few of the primary forms of cancer:

1. Carcinomas :- The cells that line the body's inner and outer surfaces are called epithelial cells, and here is where many tumors start. They are the most prevalent kind of cancer and consist of: Breast cancer - Breast cancer is a kind of cancer that usually affects women, however it can sometimes strike men. It starts in the cells of the breast. It may begin in the glands that produce milk (lobular carcinoma) or the milk ducts (ductal carcinoma), and it may spread to other areas of the body. Gender, age, family history, inherited gene variants (such as BRCA1/2), and lifestyle variables including alcohol use are risk factors. A breast lump, changes in breast size or shape, and nipple discharge are typical signs. Treatment outcomes, which may include hormone therapy, radiation, chemotherapy, surgery, or targeted therapies, are improved by early detection achieved through mammography and self-examinations. The type of breast cancer and the stage of diagnosis determine the prognosis.[11],[12],[13]



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Lung cancer- One kind of cancer that commonly starts in the cells lining the airways of the lungs is lung cancer. It is among the main reasons why people die from cancer all over the world. Lung cancer comes in two primary forms: small cell lung cancer (SCLC), which is more aggressive, and non-small cell lung cancer (NSCLC), which is more prevalent. Although smoking is the main risk factor for lung cancer, nonsmokers can also get the disease, frequently as a result of genetic predispositions, environmental contaminants, or secondhand smoke exposure. Coughing up blood, chest pain, shortness of breath, chronic coughing, and inexplicable weight loss are some of the symptoms. Since symptoms frequently don't show up until the cancer has progressed, early detection is difficult. Imaging studies, biopsies, and occasionally molecular testing are used in the diagnosis process. Depending on the stage and type of lung cancer, treatment options include immunotherapy, targeted therapy, radiation therapy, chemotherapy, and surgery.[13],[14]

Colorectal cancer (colon and rectum) :- Cancer that begins in the colon or rectum, which are sections of the large intestine, is referred to as colorectal cancer. It usually starts as polyps, which are tiny, non-cancerous growths that have the potential to evolve into cancer over time. Age (it is more common in people over 50), inherited genetic mutations (like those in the BRCA genes), inflammatory bowel diseases (like Crohn's disease or ulcerative colitis), and lifestyle factors (such as a high-fat, low-fiber diet, lack of physical activity, smoking, and heavy alcohol use) are risk factors for colorectal cancer, though the exact cause is not always known. Blood in the stool, unexplained weight loss, exhaustion, abdominal pain, and changes in bowel habits (such as diarrhea or constipation) are some of the symptoms. Regular tests, such as colonoscopies, can discover colorectal cancer early, when it is most curable. Depending on the stage and extent of the cancer, treatment frequently consists of surgery to remove the tumor, followed by chemotherapy, radiation therapy, and occasionally targeted or immunotherapy. Although early detection generally improves the prognosis for colorectal cancer, results can differ depending on the stage and other variables.[15],[16],[17]

Prostate cancer :- One kind of cancer that develops in the prostate, a little gland in males that secretes seminal fluid, is called prostate cancer. It is among the most prevalent malignancies in men, particularly those over fifty. Although the precise etiology of prostate cancer is unknown, risk factors include age, African American ethnicity, a family history of the disease, and specific genetic abnormalities. Prostate cancer frequently has no symptoms in its early stages, but when it advances, symptoms can include erectile dysfunction, lower back, hip, or pelvic pain, blood in the urine or semen, and trouble urinating.[18] Digital rectal exams (DRE), biopsy, and PSA (prostate-specific antigen) blood tests are typically used to identify prostate cancer. Depending on the stage of the disease, treatment options may include surgery, radiation therapy, hormone therapy, chemotherapy, targeted therapies, or active surveillance for less aggressive malignancies. For most men, the prognosis is good, especially if the cancer is found early, but it can change based on how aggressive and widespread disease.[19]

Pancreatic cancer:- Pancreatic cancer begins in the pancreas, an organ that regulates blood sugar and digestion. Because of the lack or ambiguity of early symptoms, it is typically discovered at a late stage. Symptoms may include abdominal pain, weight loss, jaundice (yellowing of the skin), and digestive issues such as nausea. Chronic pancreatitis, genetic mutations, smoking, obesity, and family history are all significant risk factors. The two primary types of pancreatic cancer are exocrine pancreatic cancer (which includes the most common type, pancreatic ductal adenocarcinoma) and endocrine pancreatic cancer. Imaging investigations, blood tests (such as CA 19-9), and biopsies are commonly employed in the diagnostic process. Depending on the stage of the cancer, treatment options may include radiation, chemotherapy, surgery, and targeted therapies.[20],[21]

Liver cancer:- Liver cancer, also known as hepatocellular carcinoma (HCC), develops in the liver, which is responsible for digesting nutrients and eliminating toxic substances. It is frequently associated with chronic liver illnesses such as cirrhosis, which can develop from hepatitis B or C infections, alcohol addiction, or non-alcoholic fatty liver disease. Early signs may include unexplained weight loss, stomach pain, jaundice (skin yellowing), and abdominal swelling. Chronic liver disease, obesity, diabetes, and pollutants all pose risks. Imaging studies, blood tests (such as alpha-

fetoprotein), and biopsy are all standard methods for diagnosing liver cancer. Surgery, liver transplantation, chemotherapy, radiation, or targeted medicines are all options for treatment, depending on the stage and liver function. When diagnosed at an advanced stage, the prognosis is typically bad.[22],[23]

Skin cancer :- Skin cancer is the most prevalent type of cancer and occurs when abnormal skin cells multiply uncontrollably. There are three main types: basal cell carcinoma, squamous cell carcinoma, and melanoma. Basal cell and squamous cell cancers are more common and usually found in sun-exposed areas, although melanoma, the most serious type, can grow anywhere on the skin. Excessive sun exposure, fair skin, a history of sunburn, and tanning bed use are all significant risk factors. Skin cancer frequently manifests as a new growth or a change in an existing mole, such as size, shape, or color changes. Early detection by self-exams and regular dermatologist visits improves the likelihood of successful treatment, which may include surgery, radiation therapy, or chemotherapy.[24]

2. Sarcomas:- These tumors develop in the connective tissues, which include cartilage, blood vessels, muscles, fat, and bones.

Osteosarcoma (bone cancer):- Bone cancer is a rare type of cancer that starts in the bones and typically affects the long bones of the arms and legs. The two main forms are osteosarcoma, which primarily affects teenagers and young adults, and chondrosarcoma, which is more common in older persons. Bone cancer can lead to discomfort, edema, and fractures in the affected bone. The exact etiology is unknown, although risk factors include inherited genetic disorders, prior radiation therapy, and certain bone diseases such as Paget's disease. Imaging studies such as X-rays, MRIs, or CT scans are typically used to make a diagnosis, which is then confirmed by biopsy. Treatment options vary depending on the cancer's location and stage, and may include surgery to remove the tumor, chemotherapy, or radiation. Early detection is critical for better results , however the prognosis can vary.[25]

Liposarcoma (fat tissue cancer):- Fat tissue cancer, also known as liposarcoma, is a rare cancer that begins in fat cells, typically in the deep tissues of the arms, legs, or abdomen. It can occur at any age, but is most commonly diagnosed in adults between 40 to 60 years old. The specific cause of liposarcoma is unknown, but certain hereditary factors and prior radiation exposure may raise risk. Symptoms may include a painless lump or swelling in the affected area, which may grow slowly and go undetected until it grows larger. Imaging studies, such as MRI or CT scans, are often used to make the diagnosis, which is then confirmed by a biopspy.

Leukosarcoma (muscle tissue cancer) :- Muscle cancer, also known as rhabdomyosarcoma, is a rare disease that originates in the skeletal muscles responsible for movement. It most typically affects children and teenagers, but it can also occur in adults. Rhabdomyosarcoma can develop in a variety of locations, including the head, neck, arms, legs, and belly. Symptoms typically include swelling, discomfort, and a noticeable lump in the affected area. The specific cause is unknown, however genetics could play a part. Imaging scans and biopsy help to make a diagnosis. Depending on the size, location, and stage of the tumor, treatment usually consists of surgery, chemotherapy, and, in some cases, radiation therapy. The prognosis is dependent on early discovery and cancer spread.[26]

3. Leukemia:- A type of cancer that starts in the bone marrow or other tissues that create blood and produces aberrant blood cells. Leukemia is a malignancy that begins in the blood-forming organs, usually the bone marrow, and causes the creation of abnormal blood cells, particularly white blood cells. These unwanted cells multiply uncontrollably, pushing out good blood cells and reducing the body's capacity to fight infections, control bleeding, and transport oxygen. Leukemia can be classified into four types: acute lymphocytic leukemia (ALL), chronic lymphocytic leukemia (CLL), acute myeloid leukemia (AML), and chronic myeloid leukemia (CML). Symptoms may include weariness, fever, recurrent infections, easy bruising or bleeding, swollen lymph nodes, and weight loss.[27]

4. Lymphomas:- A vital component of the immune system, these malignancies begin in the lymphatic system and include. Lymphoma is a cancer that develops in the lymphatic system, which is part of the body's immune system. It is the unregulated proliferation of lymphocytes, a type of white blood cell. Lymphomas are classified into two types: Hodgkin lymphoma and Non-Hodgkin lymphoma. Hodgkin lymphoma is distinguished by the presence

of Reed-Sternberg cells and is generally more curable, affecting younger people. Non-Hodgkin lymphoma is a broader term that can be more aggressive, affecting a variety of lymphocytes and organs. Symptoms typically include swollen lymph nodes, unexplained weight loss, fever, nocturnal sweats, and exhaustion. A weaker immune system, illnesses such as the Epstein-Barr virus, and a family history all increase the risk. Chemotherapy, radiation therapy, targeted therapy, and stem cell transplants are all options for treatment. The prognosis is determined by the type of lymphoma, its stage, and individual characteristics.[28]

5. Melanoma:- A kind of skin cancer that starts in the cells called melanocytes that produce pigment. Compared to other forms of skin cancer, it is frequently more aggressive. Melanoma is a form of skin cancer that develops in melanocytes, the cells that produce pigment (melanin) in the skin. It frequently forms in existing moles or shows as new dark spots on the skin. Melanoma is more aggressive than other types of skin cancer and can spread throughout the body if not caught early. Excessive sun exposure, tanning bed use, fair skin, a history of sunburns, and a family history of melanoma are all significant risk factors. Early indications include changes in the size, shape, and color of moles. Surgery is often used to treat the condition, although advanced stages may also entail immunotherapy, targeted therapy, or chemotherapy. Early detection is critical for improved outcomes.[29]

6.Cancers of the Central Nervous System (CNS):- Cancers of the central nervous system (CNS) originate in the brain or spinal cord. These malignancies can be primary, starting in the CNS, or secondary, spreading to other regions of the body. There are several forms of primary CNS malignancies, including gliomas, meningiomas, astrocytomas, and glioblastomas, the last being the most aggressive. CNS cancer symptoms vary depending on the location of the tumor and may include headaches, seizures, vision problems, balance or coordination issues, and cognitive changes. Risk factors include genetic disorders, radiation exposure, and family history. Imaging techniques such as MRI or CT scans, as well as biopsy, are often used to make a diagnosis. Surgery, radiation therapy, chemotherapy, and targeted medicines are all possible treatment choices. The prognosis is determined by the kind, size, and location of the tumour.[30]

7. Multiple myeloma:- An immune system-compromising and bone-damaging malignancy of the bone marrow's plasma cells. Multiple myeloma is a malignancy that starts in plasma cells, which are white blood cells found in the bone marrow. These malignant plasma cells generate aberrant antibodies, which can harm bones, kidneys, and other organs. Symptoms may include bone discomfort, fractures, weariness, anemia, recurring infections, and kidney difficulties. The actual cause is unknown, although risk factors include age (more common in older adults), family history, and specific genetic characteristics. Blood tests, bone marrow biopsies, and imaging examinations are used to determine the diagnosis. Chemotherapy, targeted treatments, stem cell transplants, and immunotherapy are frequently used as treatment options. While not a cure, therapy can aid with symptom management and quality of life.[31]

8.Neuroendocrine Tumors: These malignancies start in the specialized hormone-producing cells known as neuroendocrine cells. Neuroendocrine tumors (NETs) are an uncommon type of cancer that starts in neuroendocrine cells, which are specialized cells that create hormones and can be found throughout the body, including the lungs, pancreas, and gut. NETs can be functional, which means they produce excess hormones that cause symptoms such as flushing, diarrhea, or high blood pressure, or nonfunctional, which means they do not cause symptoms until they expand in size. Symptoms vary depending on the tumor's location and hormone output. Imaging studies, blood tests (such as those for particular hormones), and biopsies are commonly used in the diagnosis process. Surgery, radiation therapy, chemotherapy, and targeted medicines are all viable treatment choices. NETs can grow slowly, however aggressive versions do exist. Early detection is critical for achieving better outcomes and treating symptoms.[32]

9.Head and Neck malignancies: These malignancies can affect the mouth, throat, larynx (voice box), or nose and are located in the head or neck area. Head and neck malignancies are tumors that occur in the mouth, throat, larynx, sinuses, nose, and salivary glands. These malignancies are frequently connected to risk factors such as smoking, binge drinking,

HPV infection, and poor oral hygiene. Symptoms can include a chronic sore throat, difficulty swallowing, hoarseness, neck lumps, mouth sores, and unexplained weight loss. Imaging studies, biopsies, and physical examinations are commonly used to make diagnoses. The location, size, and stage of the cancer determine the treatment options, which may include surgery, radiation therapy, chemotherapy, or a combination of these. Early detection increases the likelihood of successful treatment, however the prognosis varies according to the kind and stage of cancer.[31],[32]

How to helps Nanoparticles treatment in Cancer therapy?

Nanoparticle-based cancer therapies have considerable advantages in terms of precision, effectiveness, and safety. Here's how nanoparticles aid cancer treatment;

Target Drug Delivery System: Nanoparticles can be created to precisely target cancer cells. Nanoparticles can carry chemotherapy or other medications directly to the tumor by attaching molecules to their surfaces that link to cancer cell receptors. This increases the concentration of the medicine at the cancer location, allowing for greater therapy efficacy while protecting healthy cells. This focused strategy reduces the widespread harm associated with standard chemotherapy.[33]

Overcoming Drug Resistance: One of the most significant obstacles in cancer treatment is drug resistance, which occurs when cancer cells become less sensitive to traditional medicines. Nanoparticles can bypass the mechanisms that cancer cells utilize to reject medications, ensuring that therapies are effective. Their capacity to enter the tumor microenvironment and deliver medications more efficiently aids in combating this resistance.[33]

Improved Drug Solubility: Many cancer medicines have poor solubility, which reduces their absorption and effectiveness. Nanoparticles can encapsulate these medications, making them more soluble and easier to ingest. This improves the overall pharmacokinetics of the medications, allowing them to reach the tumor more efficiently.

Reduced Side Effects: Nanoparticles protect healthy cells from hazardous substances by delivering medications directly to the tumor location. This precision lowers the risk of severe adverse effects like hair loss, nausea, and immunological suppression, which are prevalent with traditional treatments.

Enhanced Imaging and Diagnosis: Nanoparticles can also be utilized in diagnostic imaging. They can transport imaging chemicals, such as contrast dyes, which improve tumor visibility in medical scans like MRIs and CT scans, allowing for more accurate diagnosis and treatment planning.

Combination Therapies: Nanoparticles can carry numerous therapeutic chemicals at once, allowing for combination therapies that target cancer cells in different ways, enhancing therapy success.[33],[34]

What is Nanoparticles?

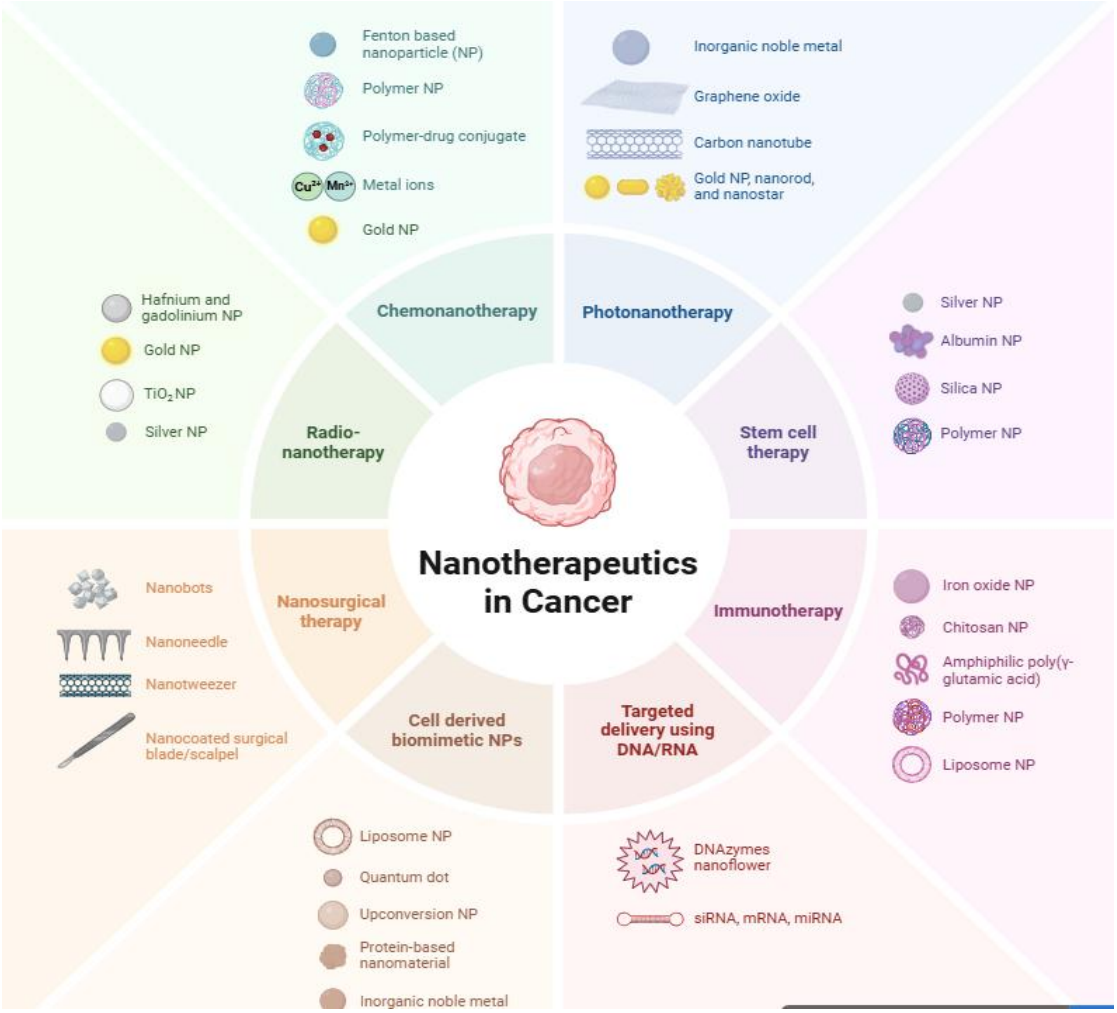
Technically speaking, nanoparticles (NPs) are particles with a single dimension of less than 100 nm and special qualities that are typically absent from bulk samples of the same substance. These nanoparticles can be categorized as 0D, 1D, 2D, or 3D based on their general shape. Nanoparticles have a somewhat complex basic composition that includes the shell, the surface layer and the core, which is sometimes referred to as the NP itself and is essentially the major part of the NPs. These materials have become very important in interdisciplinary domains because of their remarkable qualities, which include increased targeting system, dissimilarity, sub-micron size and high surface:volume ratio.[35],[36]

Another name for nanoparticles is 'zero dimensional' nanomaterials. In contrast to one-dimensional nanomaterials, which have one dimension larger than the nanoscale (like nanowires and nanotubes), and two-dimensional nanomaterials, which have two dimensions larger than the nanoscale (like self-assembled monolayer films), this definition results from the fact that all of their dimensions are in the nanoscale.[37]

Nanoparticles have many advantages in contemporary medicine. In fact, there are some situations in which nanoparticles make it possible to conduct studies and treatments that would otherwise be impossible. But nanoparticles also present special social and environmental problems, especially when it comes to toxicity. The main contributions in nanoparticles to contemporary medicine will be highlighted in this overview, together with the social

and environmental implications of their application.[38]

Deep tissue penetration of NPs has been shown to promote the increased permeability and retention (EPR) effect. Additionally, the surface properties influence half-life and bioavailability by successfully overcoming epithelial fenestration. For instance, NPs coated with the hydrophilic polymer polyethylene glycol (PEG) reduce opsonization and evade immune system clearance. Additionally, by adjusting the properties of particle polymers, the release rate of medications or active moiety can be optimized. All things considered, the distinctive properties of NPs control their therapeutic impact in the management and treatment of cancer.[39],[40]



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Types of Nanoparticles

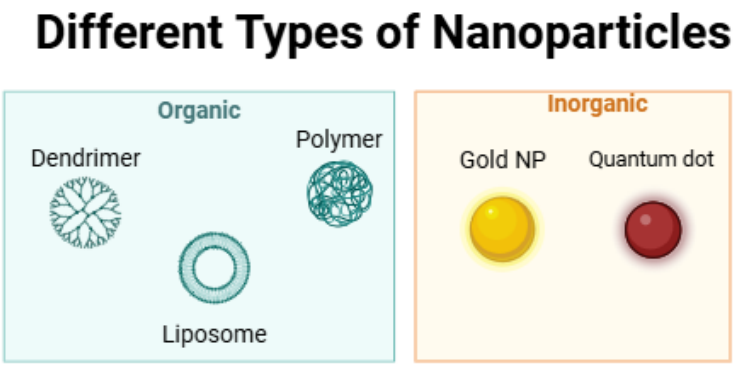

Fig:3.0

1. Liposomes:- These spherical vesicles, which can be uni- or multi-lamellar, are made of phospholipids and are used to encapsulate medicinal molecules. Liposomes are special because of their biological inertness, minimal intrinsic toxicity, and weak immunogenicity. The first medicine at the nanoscale to be licensed was liposomes in 1965. A "hydrophilic core" and a "hydrophobic phospholipid bilayer" make up a typical liposome structure. They can successfully preserve the entrapped medicine from environmental deterioration in circulation by entrapping aquatic and aqueous pharmaceuticals thanks to their special architecture. [41]

Liposomes exhibit superior anti-tumor activity and increased bioavailability, making them an ideal vehicle for the administration of drugs including doxorubicin, paclitaxel, and nucleic acid. Two authorized liposome-based daunorubicin formulations for the treatment of MBC are Doxil® and Myocet®. However, the use of liposome-based NPs is restricted because of drawbacks such as reduced encapsulation efficacy, rapid removal by MP, cell adsorption, and short shelf life.[42]

2. Polymeric Nanoparticles:- A clear definition of polymeric nanoparticles (PNPs) is "colloidal macromolecules" having a particular structural makeup made up of several monomers. To accomplish controlled drug release in the target, the drug is either encapsulated or affixed to the outside of NPs, forming a nanosphere or a nanocapsule. PNPs were first composed of non-biodegradable materials such polystyrene, polyacrylamide, and polymethylmethacrylate (PMMA) . However, because it was difficult to remove them from the system, their accumulation resulted in toxicity. Nowadays, biodegradable polymers that are known to improve medication release and biocompatibility and lessen toxicity include polylactic acid, poly(amino acids), cellulose, alginate, and albumin. Research has demonstrated that coating PNPs using polysorbates and employing the surfactant impact of polysorbates can achieve this. External coating improves NPs' interactions with the blood–brain barrier's (BBB) endothelial cell membrane. According to a study, indo methacin-loaded nanocapsules significantly reduced tumor growth and increased survival in a rat xenograft glioma model. With over 10 polymeric nanoparticles containing anticancer medications undergoing clinical development, this is a rapidly expanding sector. Examples include HPMA copolymer-DACH-platinate (AP5346), HPMA copolymerplatinate (AP 5280), HPMA copolymerplatinate-paclitaxel (PNU166945), PEG-camptothecin (Prothe can), Modified dextran-camptothecin (DE 310), and HPMA copolymerplatinate-doxorubicin galac tosamine (PK2).[43],[44]

3. Dendrimers:- The term "dendrimer" comes from the Greek word "Dendron," which means "tree." Dendrimer is also known as 'Arborols', which comes from the Latin word 'arbor' and means 'tree' or 'Cascade molecule'. Dendrimers are repetitively branched molecules with a monomer unit connected to the center, resulting in a monodisperse, tree-like, star-shaped structure with diameters ranging from 2 to 10 nm. Dedrimer with minimal polydispersity and good functionality. A dendron typically has a single chemically accessible group known as the focus point (branching points).[45]

4. Quantum Dots:- Quantum dots (QDs) are nanometer-sized semiconductor particles with unique optical and electrical capabilities due to their small size, which typically ranges between 1 and 10 nanometers. These qualities derive from quantum confinement, which restricts electron movement and creates discrete energy levels. As a result, quantum dots can absorb and emit light at different wavelengths based on their size and material composition. Their tunability makes them useful in a variety of applications, including displays, solar cells, and biological imaging. Their large surface area and increased fluorescence make them useful for sensing applications. Cadmium selenide (CdSe), lead sulfide (PbS), and indium phosphide (InP) are all materials that can be used to make quantum dots.[46]

5. Silica Nanoparticles:- Silica nanoparticles are small particles of silicon dioxide (SiO_2) that range from 1 to 100 nanometers in size. Because of their large surface area, stability, and biocompatibility, they are frequently used in fields like as medicine, electronics, and materials research. In medicine, they are used as drug delivery systems, imaging agents, and diagnostics. In material science, they improve the characteristics of composites, coatings, and ceramics. Their ability to create porous structures makes them helpful for catalysis and adsorption. Silica nanoparticles can be designed for specific applications by manipulating their size and surface characteristics.[47],[48]

Approval (Year)	Product	Company	Nanoparticles Material	Drug/Mechanism	Indications
1995	Doxil® (Doxorubicin Liposome Injection)	Janssen Pharmaceuticals	Distearoylphosphatidylcholine (DSPC) and cholesterol and Polyethylene glycol.	Liposomal formulation of Doxorubicin for targeted drug delivery	Ovarian cancer, Breast cancer, Multiple myeloma,
2005	Abraxane® (Albumin-Bound Paclitaxel Nanoparticle)	Celgene Corporation (now Bristol-Myers Squibb)	Albumin-bound nanoparticles	Paclitaxel bound to albumin for improved solubility and delivery	Breast cancer, Non-small cell lung cancer, Pancreatic cancer
2013	Lipoplatin (Liposomal Cisplatin)	Super Gen (now Astex Pharmaceuticals)	Lipid-based nanoparticle formulation of cisplatin	Liposomal cisplatin for targeted chemotherapy	Non-small cell lung cancer, Pancreatic cancer, Ovarian cancer
Ongoing (Clinical trials)	NBTXR3 (Hensify)	Nanobiotix	Crystalline nanoparticle	Enhances radiotherapy by increasing tumor absorption of radiation	Head and neck cancer, Pancreatic cancer
Ongoing (Clinical trials)	mRNA-4157/V940	Moderna and Merck	Solid lipid nanoparticles encapsulating mRNA	Personalized cancer vaccine based on tumor-specific antigens	Melanoma, Non-small cell lung cancer (NSCLC)

Clinical Trials (Nanoparticles use for the treatment of Cancer therapy):-

The fundamental measure of nanotechnology effectiveness in medicine and oncology is the ability to efficiently translate scientific discoveries into clinical applications for improved disease diagnosis and therapy. Although nanotechnology for cancer diagnosis and therapy is still in its early stages, some nanocarrier-based medications are now on the market, and many more nano-based treatments are in clinical studies. Nanotechnology in cancer refers to the use of precisely tailored materials to create novel therapeutics and devices that may reduce toxicity while also improving therapy efficacy and delivery. Notably, the most well-known nano-based medications, Doxil® and Abraxane®, were approved by the FDA several years ago and have been successfully utilized in clinical practice. A detailed list of cancer nanotherapeutics approved by the FDA and other nations' regulatory agencies is provided. Clinical Trials.gov provides a complete list of current U.S. clinical trials addressing cancer nanotechnology.[49],[50]

AI Involvment Nanoparticles in Cancer Therapy

Artificial intelligence (AI) is transforming nanoparticle-based cancer treatment by boosting drug delivery, increasing treatment precision, and optimizing diagnostics. By combining AI and nanomedicine, researchers can create targeted therapeutics that reduce damage to healthy tissues while enhancing cancer therapy efficacy. Traditional cancer treatments, such as chemotherapy, impact both malignant and healthy cells, resulting in significant side effects. AI aids in the design of nanoparticles that transport medications directly to cancer cells, hence lowering toxicity. Machine learning methods use patient data to forecast the ideal size, shape, and composition of nanoparticles, ensuring that they reach the tumor successfully. AI also aids in drug release control, ensuring that medication is delivered at the appropriate time and location in the body. Cancer cells frequently develop medication resistance, making treatment less effective with time. AI detects patterns in tumor behavior and aids in the development of adaptive nanoparticles capable of overcoming medication

resistance.[51] By continuously evaluating patient reactions, AI can advise changes to nanoparticle formulations, assuring long-term therapy success. AI-powered imaging improves the early detection of cancers. Nanoparticles serve as contrast agents in MRI and CT images, increasing accuracy. AI algorithms analyze imaging data to spot abnormalities that the human eye might overlook, enabling for earlier and more accurate cancer diagnosis.[52]

Cancer treatments are getting smarter, safer, and more successful as AI and nanotechnology combine, paving the way for a future of customized medicine in which each patient receives treatment matched to their own cancer profile.[52]

Advantages of Nanoparticles in Cancer Therapy

A completely new era in cancer diagnosis, treatment, and management has been ushered in by the application of nanotechnology. NPs increase the intracellular concentration of medications without causing harm to healthy tissue through active or passive targeting. To create and control the drug release, the targeted NPs can be modified to be either pH-sensitive or temperature-sensitive.

Drugs within the alkaline TME can be delivered using the pH-sensitive system for drug delivery. In a similar manner, temperature changes introduced by sources like as magnetic fields and ultrasonic waves cause the temperature-sensitive NPs to release the medications at the desired location. Furthermore, NPs' "physicochemical characteristics," which include their size, shape, molecular mass, and chemistry of the surface, play a crucial role in the intended drug delivery system. Additionally, NPs can be utilized to target a specific moiety and can be altered based on the target[53],[54].

Due to their unequal dispersion and cytotoxicity, standard radiation therapy and chemotherapy have a number of drawbacks in terms of effectiveness and adverse effects.

Therefore, careful dosage that efficiently destroys cancer cells without causing appreciable damage is needed. A number of fortifications must be passed by the medication in order to reach the target place. The process of drug metabolism is quite intricate. The medication must cross the TME, RES, BBB, and renal infiltration under physiological conditions. "Blood monocytes, macrophages, and other immune cells" comprise the RES, or macrophage system.[55] When the medications interact with MPS in the liver, kidneys, spleen, or lungs, "macrophages or leukocytes" are activated, which quickly eliminate the drug. This results in to the drug's brief half-life. NPs with "surface modification," like PEG, go around this process and lengthen the "drug half-life" in order to get around this. Furthermore, renal infiltration is an essential bodily function. Thus, appropriate renal infiltration reduces the toxicity that NPs induce.[56]

A unique protective mechanism called the brain-blood barrier (BBB) is designed to shield the central nervous system (CNS) from noxious and dangerous substances. The brain receives vital nutrients from "brain capillary endothelial cells," which are grouped in a wall-like pattern. Since the BBB's main job is to prevent harmful substances from entering the brain, the only chemotherapy treatments for brain cancer that are now available are intraventricular or intracerebral infusions.[57]

NPs have been shown to cross the BBB, though. NPs are now delivered by an assortment of techniques, including transcytosis, peptide-modified endocytosis, focused ultrasound, and the EPR effect.Rats' absorption of methotrexate was enhanced by glutathione PEGylated liposomes encapsulated with the drug. Since Au-NPs have been shown to aid in the transport of medications that cause apoptosis, they are frequently employed. Because they are transporters, NPs also improve medication stability by halting the encapsulated cargo's deterioration.

Furthermore, a lot of medications can be encapsulated without undergoing a chemical reaction. Nanoliquid compounds are less stable than dry solid dose forms. To improve stability, stabilizers can be applied. Using porous nanoparticles is yet another method to boost stability.[58],[59]

Extensive angiogenesis, faulty vascular architecture, and impaired lymphatic drainage are some of the distinctive pathophysiologic characteristics of tumors. These characteristics are used by the NPs to target tissue from the tumor. NPs are efficiently maintained because of the tumor tissue's decreased venous return and poor lymphatic drainage. EPR is the name given to this occurrence.

Likewise, tumor-targeting can be achieved by focusing on the surrounding tissues. There are numerous ways to give NPs, including intraocular, parenteral, nasal, and oral. NPs have a high intracellular uptake and surface-to-volume ratio. According to studies, NPs work better as drug transporters than microparticles.[60],[61],[62]

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