Overcoming Drug Resistance in Cancer Using Nanotechnology: Emerging Strategies and Therapeutic Advances

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Abstract

Cancer drug resistance is a very important issue that has restricted effective cancer chemotherapy. Such mechanisms of resistance, as changing targets of drugs, overexpression of efflux transporters, better DNA repair, inhibition of apoptosis, and altering the tumor microenvironment, gravely damage the effectiveness of current methods of treatment. The solution to such challenges has come in the form of nanotechnology, which has demonstrated the potential of overcoming such barriers, offering targeted product/drug delivery and controlled administration of drugs by means of a sophisticated nanocarrier system. This review will discuss the critical developments in the use of nanotechnology in overcoming drug resistance in cancer treatment. Particular attention is paid to nanoparticle-based suppression of efflux pumps, increase of drug bioavailability, advancing tumor-specific drug delivery, and altering the tumor microenvironment so as to benefit from treatment efficacy. There are also emerging nanomaterials, such as liposomal, polymeric nanoparticle, dendrimer, inorganic nanoparticle, and micellar based science-based formats that are likely to successfully overcome resistance mechanisms. In addition, this article provides the latest topic of reversing multidrug resistance through molecular-based innovative strategies combining older nanotechnology and the latest genetic therapies like siRNA and CRISPR/ Cas9. Lastly, the current constraints, possibilities, and plans ahead, as well as the potential of clinical translation of nanotechnology-based strategies in drug resistance to cancer, are discussed.

Introduction

Cancer has remained one of the most significant health emergencies globally, and it has a significant impact on the quality of life of the patients, as well as challenging the healthcare systems with a significant economic burden. Even though significant progress has been made in the field of treatment in the forms of surgery, radiation therapy, and chemotherapy, drug resistance has become an essential setback in the realization of long-lasting success in treatment (Holohan et al., 2013; Bukowski et al., 2020). The property of drug resistance, the reduced responsiveness of cancer cells to chemotherapy, may be acquired during drug treatment or naturally present in the body, which is one of the main causes of relapse and the development of metastases (Bukowski et al., 2020).

The drug resistance mechanisms are complex and multifactorial that including genetic and epigenetic additions, activated survival routes, improved drug elimination, drug targeting, and mutation, facilitated mismatching repair of DNA damage, and tumor microenvironment (TME) (Housman et al., 2014). Interestingly, multidrug resistance (MDR) is a known entity of all these mechanisms, and the MDR is mediated by ATP-binding cassettes (ABC) transporters, particularly P-glycoprotein (P-gp), multidrug resistance-associated proteins (MRPs), and breast cancer resistance protein (BCRP), which reduces the clinical efficacy of anticancer agents (Wang et al., 2019; Sharom, 2008).

Widespread though it is, conventional chemotherapy displays cytotoxicity that is not selective enough, so it destroys large quantities of healthy tissue and is unlikely to induce adequate drug concentrations to reach cancerous regions because of low bioavailability and rapid clearance (Maeda et al., 2013). These shortcomings require the formulation of specific and precise therapeutic techniques to alleviate drug resistance, increase the efficiency of drug delivery. Nanotechnology has, however, developed as a revolutionary method in the last few years, providing new therapies to circumvent these pathological difficulties by target specificity, release control, and enhanced drug stability (Patra et al., 2018).

Cancer therapy Because nanoparticles (NPs) can be applied in the form of liposomes, polymeric micelles, dendrimers, inorganic nanoparticles, and quantum dots, nanotechnology has transformed cancer therapy due to its capabilities of targeted drug delivery, bypassing biological barriers, increasing therapeutic index of chemotherapeutic agents against cancer, and modulating immunomodulatory activity (Malam et al., 2009; Wicki et al., 2015). The nanocarriers are benevolently evaded by drug resistance through intracellular amassing of drug levels, blocking efflux transporter exercise, controlling individual tumor microenvironment, and encouraging synergistic drug confluences (Kapse-Mistry et al., 2014; Saraswathy & Gong, 2013).

Conventional Cancer Treatments: Assessing Progress and Unmet Promises

Cancer treatments have advanced a lot in recent decades; nonetheless, there are still multiple issues in the preferred treatment of this complicated illness. Surgery, chemotherapy, and radiation therapy remain the mainstays of cancer care. Although they are widely used and somewhat effective in some instances, these traditional methods of treatment are fairly limited, particularly in more developed kidney cancer cases, and thus not a valid option to ensure long-term remission and/or recovery (Van der Wal et al., 2020).

1. Chemotherapy and Drug Resistance

The mainstay in the treatment of cancer over the past several decades is chemotherapy, which is based on cytotoxic agents, a non-selective attack on any rapidly dividing cells. Although such chemotherapy has been effective in the treatment of various forms of cancer, it has various demerits. All drugs used in chemotherapy have a non-specific character and damage a large number of healthy cells, which explains the severe side effects (nausea, immunosuppression, anemia, and alopecia) of this treatment method (Sarkar et al., 2020).

Overexpression of efflux transporters, P-glycoprotein (P-gp), is the most notable process of chemotherapy resistance; P-gp is the pump that actively pumps chemotherapeutic drugs out of cancer cells, thus preventing the build-up of drugs in the cancer cells (Ambudkar et al., 1999). Moreover, cancer cells can also experience genetic mutation and, therefore, increase their survival chances and repair the chemotherapy-associated damage better (Zhang et al., 2016).

2. Radiation Therapy: Challenges and Limitations

The other basic treatment modality is radiation therapy, whereby high-power radiations are directed at the cancerous cells to destroy them. Though it is used quite well in treating local cancers, radiation therapy cannot differentiate between cancer and normal tissues; hence, it has its limits. Because this therapy is non-specific, it causes collateral damage due to the normal tissues around the target (Zaorsky et al., 2019), which causes both acute and long-term toxicities. More so, it may develop radiation resistance in multiple ways; by increasing the repair

of DNA, changing the apoptosis signaling pathway, and modifying the tumor microenvironment to incur treatment-resistant phenotypes (Huang et al., 2014).

3. Surgical Treatment and Recurrence

Operable and localized solid tumor surgery is always used. Nevertheless, surgical intervention also presents problems with the consequences of the surgery, the possibility of developing an infection, and ensuing failure to eliminate all tumor cells that cause recurrence (Baker et al., 2015). The tumor is not completely removed in a few instances, and this causes residual disease, making it recurrent and metastasized. Also, surgery can only be used on certain stages of cancer, and the likelihood of complications rises with increasing stages of cancer (Pech et al., 2020).

4. Addressing the Limitations of Conventional Therapies

Despite the large benefit brought about by conventional cancer treatment methodologies in lowering the cancer mortality rates, there is a need to address the limitations that the alternatives have in the efficacy, specificity, and side-effect profiles of the treatment through the development of cancer treatment alternatives. Nanotechnology, which is emerging, is showing great potential in addressing these constraints. Nanoparticles often have improved designs to specifically target cancer cells, improving the delivery of chemotherapy and respecting the normal cells (Malam et al., 2009). Moreover, nanotechnology could be used to prevent drug resistance, since it would alter the tumor microenvironment, increase drug uptake, and block efflux pumps (Saraswathy & Gong, 2013).

Nanotechnology for Accurate Cancer Treatment

The advancement of nanotechnology has changed many spheres of medicine, with special emphasis on cancer therapy. The use of nanoparticles (NPs) in cancer treatment, commonly known as nanomedicine, has received significant interest by virtue of its ability to address most of the drawbacks associated with conventional cancer therapies. Nanotechnology presents a versatile solution towards fighting cancer, and several strategies have been devised towards enhancing the delivery of drugs, improving the specificity of treatment, and reversing multidrug resistance (MDR) (Barenholz, 2012).

1. Precision Medicine and Nanotechnology

Precision medicine is a new mode of cancer treatment that customizes treatment to the genetic profiles of the patient, the nature of the tumor, and other molecular profiles. The goal of this approach is to have a maximization of therapeutic, and minimization of tissue damage. Nanotechnology and precision medicine are the most promising areas of the future of cancer treatment. The unusual size and surface characteristics of nanoparticles make it possible to

ensure that the drug will be transported only to the cancer cell, which will eliminate the threat of off-target effects and will increase the presence of the medication in the body (Shi et al., 2017).

2. Nanoparticle-Mediated Overcoming of Multidrug Resistance

One of the problems in cancer treatment is the problem of Multidrug resistance (MDR). MDR happens when cancer cells form resistance to a wide range of anti-cancer drugs. MDR is mainly due to overexpression of efflux transporters, which extracellularly push the drug out of their cells, so that there cannot be a drug build-up, unlike the wild type, because of this, no further successful treatment can be performed (Ambudkar et al., 1999).

Nanocarriers have been tailored to avoid the efflux pumps by increasing uptake of the drug and causing it not to be removed (Hernandez et al., 2020). Polymeric nanoparticles and liposomes have been used in this regard (Hernandez et al., 2020). As such, for instance, the folate-functionalized nanoparticle can target the folate receptor-overexpressing cancer cell, which enhances endocytosis and drug internalization, leading to better cytotoxic effect of the chemotherapeutic drugs (Saraswathy & Gong, 2013).

3. Modulating the Tumor Microenvironment

It is important that the tumor microenvironment (TME) enhances cancer advancement and therapeutic tolerance. TME is a rather hostile, heterogeneous environment, and low oxygen concentration (hypoxia), elevated interstitial fluid pressure, and acidic pH can interfere with the effectiveness of cancer treatment (Jain, 2014).

As an example, nanoparticles may be constructed to alter the TME acidic pH by deposition of alkaline particles and stabilize and increase the performance of drugs that are sensitive to pH conditions (Wicki et al., 2015). Nanoparticles have the capacity to load oxygen-carrying molecules or photosensitizing agents that can be externally triggered (light) to produce reactive oxygen species (ROS) and enhance tumor oxygenation, thus sensitizing tumors against treatment (Liang et al., 2019).

4. Theranostics: Combining Therapy and Diagnostics

A similar idea of developing theranostics, i.e., the combination of the therapeutic and diagnostic capabilities into one platform, a nanoparticle, has become the interest of great interest in the cancer treatment field. Theranostic nanoparticles not only help the exact delivery of drugs but can also help in the real-time monitoring of treatment and tumor response. The combination of these two possibilities can considerably improve personalized treatment of cancer because it can help to learn more about the efficacy of drugs and make appropriate dose adjustments (Kumar et al., 2016).

Engineered nanoparticles that possess imaging agents, e.g., quantum dots or superparamagnetic iron oxide nanoparticles (SPIONs), can give high-resolution imaging to monitor in vivo distribution and accumulation of drugs. These allow the clinicians to see tumors and how effective therapy is in real-time (Jin et al., 2016).

Targeting Nanoparticles Molecularly and Ligand-Based for Accurate Cancer Treatment

The effective use of nanotechnology in the treatment of cancer is highly determined by the possibility of localizing the cancer cells without causing much harm to non-diseased cells. This is done in two main strategies: passive and active targeting. Passive targeting is based on the fundamental properties of tumor vasculature, and active targeting applies to functionalized nanoparticles that are programmed to recognize particular cancer cell markers and bind to them. Both of the strategies possess certain strengths and weaknesses, and the current research focuses on the enhancement of these methods to achieve better treatment effects.

1. Passive Targeting: Enhanced Permeability and Retention Effect

The Enhanced Permeability and Retention (EPR) effect is among the most commonly used mechanisms in targeted drug delivery. The phenomenon can be attributed to the characteristics of the tumor blood vessels that tend to be leaky and permit the presence of nanoparticles within the tumor tissue. The vascular endothelium was highly permeable due to the overgrowth and abnormal blood vessel formation of the tumor, which enables nanoparticles to be extravasated more easily compared to normal tissues (Jain, 2017).

It is through the EPR effect, nanoparticles, especially those engineered as liposomes, micelles, and nanoparticles, achieve increased accumulation in the tumor region, which enhances the drug concentration in the desired region and decreases the systemic poisoning (Davis et al., 2013).

2. Active Targeting: Ligand-Functionalized Nanoparticles

Passive targeting has shortcomings compared to active targeting, which makes use of special ligands that bind to overexpressed receptors or antigens on cancer cells. This strategy targets the mechanism of a receptor-mediated endocytosis, where nanoparticles functionalized with specific targeting molecules, e.g., antibodies, peptides, or small molecules, can selectively bind to the surface marker of the tumor (e.g., receptor), which helps to internalize the drug-loaded nanoparticle (Khan et al., 2023).

Various classes of ligands have been investigated in active targeting of cancer cells, namely monoclonal antibodies, aptamers, short peptides, and even small-molecule drugs. The use of monoclonal antibodies, i.e., trastuzumab, in HER2-positive breast cancer can be employed in the targeted delivery of nanoparticles to a certain type of cancer cells (Sun et al., 2022).

Synthetic oligonucleotides with high affinity to a specific target, the so-called aptamers, are another strategy that has shown potential as an active targeting method. They have demonstrated that aptamers can specifically bind tumor-specific antigens with a high degree of specificity, stability, and are easily produced, as compared to antibodies (Trivedi et al., 2024).

3. Tumor-Specific Antigens and Targeted Nanoparticles

Targeted cancer treatment has become a priority owing to the use of tumor-specific antigens (TSAs) and tumor-associated antigens (TAAs). TSAs are the characteristics of cancer cells, and TAAs are the Type I, same thing being overexpressed in tumor cells compared to normal tissues, hence they are the optimal target to be aimed at by active nanoparticle-based drug delivery systems. It is expected that targeting these antigens with functionalized nanoparticles allows a high degree of specificity, which is a significant factor that minimizes the risk of off-target effects and subsequent normal tissue injury (Zhou et al., 2019).

At the same example, nanoparticles have been used to target the particular prostate-specific membrane antigen (PSMA) that is highly expressed on prostate cancer cells, in order to facilitate drug delivery to the prostate cancer cells and minimize side effects. Docetaxel-loaded nanoparticles functionalized through PSMA have also demonstrated significant success in preclinical experiments, using the drug to increase its therapeutic index (Wang et al., 2022).

4. Dual-Ligand Targeting

Recent developments also examined the use of dual-ligand targeting, in which nanoparticles are conjugated with two diverse ligands to enhance specificity and to avoid the shortfalls inherent with the targeting of individual antigens. This method harmonizes with the capabilities of various ligands, including antibodies and small peptides, to guarantee a more detailed and efficient process of targeting a tumor. Dual-ligand systems also have potential benefits in solving the potential problem of heterogeneous antigen expression in tumors, a relatively intractable problem in cancer therapy (Zhao et al., 2021).

5. Challenges and Future Directions

Although ligand-based targeting provides a high potential in enhancing the treatment of cancer, some challenges need to be solved. Among them, the fact that tumor markers can be diverse in various patient groups, as well as in one and the same tumor, creating difficulties in designing universal targeted therapy, is one of the key issues (Sun et al., 2022).

Additionally, effective internalization of a nanoparticle once it has bound to the cancer cell surface is a challenge, given that not all nanoparticles are probably internalized into the cells after effective binding to the target antigen.

Integrated Cancer Screening and Treatments Using Nanoparticles (Nanotheranostics)

Nanotheranostics refers to the combination of diagnostic and therapeutic capabilities into a single nanoparticle platform and is one of the most promising directions of cancer treatment. It has been recently seen that nanotheranostics facilitates the concurrent delivery of cancer therapy and real-time monitoring of the progress of the treatment by improving personalization and effectiveness of treatment in cancer. By uniting diagnostic and therapeutic features in nanoparticles, this method enables addressing early detection, specific tumor location, control of therapeutic response, and side effects, all of them in one, multifunctional system (Gao et al., 2018).

1. Nanotheranostic Platforms: Combining Imaging and Therapy

Nanotheranostic systems combine imaging delivery (e.g., quantum dots, magnetic nanoparticles, and gold nanoparticles) into therapeutic applications (e.g., liposomes, micelles, and dendrimers). They are designed with these platforms not just to deliver drugs in a precise manner, but also to drive the possibility to be able to image these nanoparticles in vivo, as well as to see how they are distributed and where they accumulate within the tumors. The two functionalities enable clinicians to monitor the progress of treatment and modify dosage in real time to guarantee the best therapeutic results (Malam et al., 2009).

As an example, SPIONs, often utilised in magnetic resonance imaging (MRI), may be loaded with chemotherapeutics and applied to treatment and imaging (Sung et al., 2021). SPIONs offer tumor imaging at high resolutions, and therefore, these contrast agents offer precise tumor localization besides they also offer highly targeted chemotherapy of the tumor itself, as healthy tissues are designed to minimize damage.

2. Targeted Drug Delivery with Nanotheranostics

Nanotheranostic nanoparticle can be designed in a way that they are specific to tumor markers, which means that they can give a specific delivery of chemotherapeutic drugs or other therapeutic agents. The localized intervention will enhance the drug effect, maximise the drug in the tumor, and reduce the systemic toxicity. Those nanoparticles have the possibility to be functionalized with ligands (antibodies, peptides, or small molecules) on their surface, bind specifically to overexpressed receptors on cancer cells, and select the delivery of drugs (Patra et al., 2018).

Besides application to provide conventional chemotherapy, nanotheranostic systems are seeing greater application in providing gene therapies and immunotherapies. As another example, nanoparticles may be packed together with small interfering RNA (siRNA) to suppress resistance genes or alter the immune system by directly injecting immune checkpoint inhibitors or cancer vaccines into the tumor (Yin et al., 2020).

3. Monitoring Tumor Progression and Drug Response

The most beneficial feature of nanotheranostics is real-time tracking of tumor progression and the therapeutic response. Although conventional methods of imaging may be useful in establishing the size and localization of a tumor, the rate of sensitivity and specificity may not offer the desired results in the timely identification of response to treatment or recurrence of the disease, quite effectively. The nanotheranostics nanoparticles, in their turn, provide high sensitivity and specificity of imaging, which enables the early onset of tumoring and even real-time evaluation and analysis of treatment efficiency (Wang et al., 2019).

Nanoparticle combined with Positron Emission Tomography (PET) and Single-Photon Emission Computed Tomography (SPECT) image provides very accurate tumor localization and real-time drug delivery property on a cellular level (Zhou et al., 2020).

4. Nanotheranostics for Personalized Cancer Treatment

Nanotheranostics has one of the highest strengths, which is the ability to enable personalized medication. Nanotheranostic systems would provide a combined diagnostic and treatment platform to allow the clinician to design methods of treatment that best suit the tumor of the individual patient. The possibility of tumor progression and drug response monitoring in real time would enable the adaptation of treatment plans according to the individual reaction of a patient toward this treatment and would result in less toxic but more effective cancer treatment (Gao et al., 2018).

As another example, the multifunctional nanoparticles can be employed to deliver a chemotherapeutic agent in addition to an imaging agent that targets a given tumor marker, as in the case with HER2-positive breast cancer or when EGFR is in lung cancer. Monitoring with the accuracy of drug delivery enables a more effective treatment plan and decision-making process, which leads to improved outcomes for patients (Mody et al., 2018).

5. Challenges and Future Perspectives

Irrespective of the considerable promise of nanotheranostics, there still exist a number of burdens on the clinical translation of capable technologies. Among the principal problems, there is the scale-up production of safe and efficacious nanotheranostic nanoparticles with which human health will be safe. The manufacturing process should guarantee good functional properties of nanoparticles, that is, specific targeting, drug loading capability, and stability when a large dosage is synthesized (Malam et al., 2009).

The long-term toxicity of nanoparticles and biocompatibility is another issue. Although the nanoparticles have been seen to perform well under preclinical testing, their safety is yet to be fully established in terms of long-term effects on humans. The possibility of being accumulated in the non-target tissues and the activation of the immune system or even the toxicity remains a concern that has to be clarified in future studies (Barenholz, 2012).

Nanomaterial-Based Formulations for Reversing Multidrug Resistance

Cancer cells acquire resistance toward a diverse set of chemotherapeutic agents, and multidrug resistance (MDR) continues to be a major impediment in the treatment of cancer. The underlying pathways of MDR are multifactorial and complex, involving overexpression of efflux pumps, drug targets, repairing of DNA repair, and changes in the apoptosis pathways (Holohan et al., 2013). This necessitates the need to find ways of overcoming MDR in the effort to enhance the overall effectiveness of chemotherapy to avoid the possible recurrence of cancer. Nanotechnology, especially nanomaterials, provides new strategies to deal with MDR via enhanced drug carriage and inhibition of drug efflux or regulation of resistance at the nano-molecular level.

1. Nanoparticles for Overcoming Efflux-Mediated Drug Resistance

The active extrusion of anticancer drugs by ATP-binding cassette (ABC) transporters is one of the most established of MDR mechanisms, and these transporters include P-glycoprotein (P-gp), multidrug resistance-associated proteins (MRPs), and breast cancer resistance protein (BCRP) (Ambudkar et al., 1999). Nanoparticles thus have been seen as a probable solution to this issue in that they can adjust the intracellular uptake of drugs and counteract efflux pumps.

Chemotherapeutic agents have been encapsulated in the polymeric nanoparticles, liposomes, and micelles to protect against efflux pumps, thereby enhancing drug retention in cells of interest. These nanocarriers can also able to be made functional with special ligands to target overexpressed proteins on cancerous cells so that the drug selectively enters the cell (Patra et al., 2018).

Recent investigations have demonstrated that nanoparticles (e.g., gold nanoparticles and lipid-based carriers) have the ability to reverse MDR effectively by increasing the accumulation of drugs in resistant cells. Such nanoparticles prevent the action of efflux pumps, enhance endocytosis, and intracellular storage, so that the drugs delivered to the target site work more efficiently (Zhao et al., 2019).

2. Nanoparticles for Targeting Drug Resistance Mechanisms

Besides lotting out efflux pump activity, development of nanoparticles targeting other molecular processes underlying MDR, such as delivery to inhibited altered drug targets, DNA repair pathways, or survival signaling pathways, is also established. Engineering nanoparticles can aid the delivery of a small interfering RNA (siRNA) and antisense oligonucleotide to silence genes that encode the MDR, such as DNA-resistant targets or repair proteins (Xu et al., 2019).

SiRNA-loaded nanoparticle has been really promising in this regard as it is able to target specifically the genes that cause MDR. As one example, the downregulation of P-gp or BCRP by

nanoparticle-mediated siRNA delivery can result in chemo-sensitization of cancer cells (Sankar et al., 2025). By inhibiting the expression of these proteins, nanoparticles can activate the apoptotic pathway, thus transforming the resistant cancer cells to become more vulnerable to chemotherapy (Chen et al., 2020).

3. Gene Editing Approaches to Overcome MDR Using Nanomaterials

Convergence of nanomaterials and gene editing technologies, like CRISPR/Cas9, stands a good chance of addressing MDR in cancer treatment. The gene responsible for fixing drug resistance, such as the gene coding drug efflux pump or a DNA repair protein, can be specifically knocked out with CRISPR/Cas9. Nanoparticles have the potential to act as delivery vehicles of CRISPR/Cas9 components, where precision in gene editing is possible in cancer cells.

Recent tests have shown that nanoparticles can effectively deliver CRISPR/Cas9 systems to the microkingdom of cancerous cells cured with chemotherapy drugs, thus making them chemotherapy-sensitive (Coelho et al., 2022). Genetically editing cancer cells is a potent concept that can be utilized in the fight against MDR on a molecular basis by addressing the actual causes behind it.

4. Modulating the Tumor Microenvironment (TME) to Reverse MDR

Tumor microenvironment (TME) is an important factor in the rise and advancement of MDR. Hypoxia, low pH, as well as altered assemblages of immune cells in the TME promote the viability of tumor cells and response to chemotherapy (Jain, 2014). Nanoparticles appear as a new method of regulating the TME, which enhances the utility of chemotherapeutic drugs and conquers resistance.

Nanoparticles can be developed to carry oxygen-carrying reagents or pH-sensitive drugs, which would normalize the physiological status of TMEs. As an example, hypoxic conditions in tumors can be relieved by nanoparticles that carry oxygen carriers to make cancer cells become more sensitive to chemotherapy and radiation (Liang et al., 2019). Likewise, nanoparticles loaded with alkaline reagents into the acidic TME can stabilize and increase the activity of chemotherapeutic drugs and cause fewer drug resistance cases (Wang et al., 2022).

5. Challenges and Future Directions

Although nanomaterial-based formulations have great potential for addressing the problem of MDR, there are a number of issues that should be resolved before they can be applied in practice. The scale-up production of safe and effective nanoparticles is one of the major challenges. The production process should provide quality, stability, and functionality of nanoparticles on a large-scale basis (Malam et al., 2009).

Biocompatibility and (chronic) nanotoxicity are another challenge. Although they show convincing results in a preclinical setting, long-term effects on the safety of humans remain a concern with nanoparticles. The problems like non-target delivery of nanoparticles to organs, theoretically known immunogenicity, and prolonged adverse effects should be thoroughly addressed during the clinical trials (Patra et al., 2018).

AI's Broad Application in Nanomedicine

Artificial Intelligence (AI) has transformed many industries, including healthcare and drug development. The combination of AI and nanomedicine would have tremendous potential to enhance the process of creating new treatments against cancer and especially to cut down the problem of drug resistance. Machine learning, deep learning, and neural networks are AI techniques that are being more widely used to maximize the design, characterization, and delivery of nanoparticles so that treatments can be personalized and clinical outcomes become higher (Zohuri, 2020).

1. AI in Nanoparticle Design and Optimization

Nanoparticle design and optimization are one of the major issues in nanomedicine. Nanoparticles should fulfill a number of requirements, such as being biocompatible, having the best size, surface charge, drug loading efficiency, and stability in biological conditions. Classical nanoparticle design is slow and is based more on trial and error. Nevertheless, AI, mainly through machine learning algorithms, can hugely speed up the design process by being used to analyze large data and predict the most effective nanoparticle properties when applied to a particular drug delivery application (Sherani et al., 2024).

The AI models are especially useful, with deep learning being the most appropriate example, because they can integrate enormous amounts of data, calculated during experimental research, to foresee the connection between the characteristics of nanoparticles and their interaction with biological systems. AI can also be used to design nanoparticles that may impair a particular resistance mechanism, like the involvement of drug efflux pumps, or tumor microenvironment remodeling (Elemento et al., 2021).

2. AI-Driven Nanoparticle Characterization

To determine the behaviour of nanoparticles in biological systems, such factors as their stability, release profile, and the way they interact with cells and tissues, it is important to characterize the nanoparticles. In the traditional characterization techniques, e.g., electron microscopy, or electron spectroscopy, it may be cost-effective as a source of information, but can be a time-consuming and expert-intensive requirement.

As an example, one can use AI algorithms to analyze images acquired with either electron microscopy or optical imaging, where the shape, size, and distribution of nanoparticles in a tissue sample can be automatically detected. AI can also enable real-time imaging of nanoparticle behavior in vivo, with the help of computer vision and pattern recognition technologies, which allows determining drug release and tumor targeting with preclinical models (Zhao et al., 2021).

3. AI in Drug Discovery and Development

AI is vital in the speed of drug discovery, especially in the creation of cancer drugs. Conventional drug search is a long, expensive, and high-failure task in clinical trials. AI models have the potential to considerably decrease the time and the cost of drug development since they can model the potential advantage of potential drug candidates, predict biomarkers of treatment, and review patient-individual data to find personalized therapy.

New drug candidates that can be loaded in nanoparticles can also be discovered using AI to be delivered in a more effective way. Using machine learning along with probing huge chemical libraries, AI can foretell which compounds are apt to work on certain sorts of cabinets or resistance pathways (Mak & Pichika, 2019).

4. Personalized Medicine and AI in Cancer Treatment

A personalized cancer treatment is also one of the most important achievements of AI in the field of nanomedicine. The goal of personalized medicine is to address the treatment approach depending on the individual patient's genetic makeup and his or her tumor-related features and responsiveness to past treatments. The potential of AI is to analyze enormous volumes of genomic, proteomic, and clinical data and design individual treatment regimens that are more likely to respond to each particular patient.

It is possible to go even deeper with personalized medicine by incorporating AI with nanotechnology. It will be possible to predict the effectiveness of both nanoparticles and drugs in treating a particular tumor of the patient with the help of AI and select the most effective therapeutic agent and nanoparticle preparations using the same (Liao et al., 2023).

5. AI in Monitoring Treatment Response and Drug Resistance

Monitoring the effectiveness of the treatment approaches is one of the most important components of cancer treatment. Conventional practices in monitoring the response to treatment, including imaging or biopsies, may be invasive and, in most cases, not adequate to detect the initial signs of drug resistance. It is possible to use AI to monitor and recognize failure of treatment as soon as possible, reading real-time data provided by different kinds of examinations, including imaging, blood tests, as well as molecular profiling.

As an example, liquid biopsy, as a form of biopsy, can be analyzed using AI, providing data on circulating tumor DNA (ctDNA) to monitor alterations in genetic mutations related to drug resistance (Guo et al., 2022). These allow resistance mechanisms to be identified in an early enough time to allow treatment regimes to be adjusted before resistance is clinically evident. Radiographic images can also be analyzed with the help of AI that will identify the slightest change in the size or metabolism of tumours, which can be a sign of resistance appearing, or tumour recurrence (Zhao et al., 2021).

6. Future Prospects and Challenges

AI can simultaneously transform cancer treatment by integrating it with nanomedicine. Nevertheless, there are a number of issues that need to be overcome prior to its wide implementation in clinical settings. Major challenges encompass the necessity to unify AI formulations and nanomaterials. To achieve successful application of personalized cancer therapies, it is necessary to make sure that predictions produced by AI are highly accurate and reliable across the various cancer types and groups of patients.

The interpretability of AI models is also another challenge. Although AI algorithms may predict on the basis of massive amounts of data, it is important to determine the reasoning behind such forecasts in order to make clinical decisions. To promote clinician trust as well as to enhance acceptance of the AI in oncology, it is essential to be able to develop explainable AI models, capable of providing insight into the treatment decision-making process (Zohuri, 2020).

Conclusion

A hopeful solution to the resistance of multidrug therapy (MDR) in cancer treatment is nanotechnology. Nanomedicine can use the intrinsic advantages of nanoparticles, i.e., they facilitate the delivery of medications and can avoid resistance, which increases the chances of treating the disease and reduces the risks of adverse effects. Nanoparticles by passive and active targeting achieve the accurate targeting of drugs to the tumor site, increasing therapeutic index and minimizing systemic toxicity. Theranostics Nanotheranostics enables real-time monitoring of the treatment response, enabling personalized cancer care.

Along with this, its combination with nanotechnology will give an effective solution to dealing with and tackling the molecular causes of MDR through gene therapies such as siRNA and CRISPR/Cas9. More so, artificial intelligence (AI) in nanoparticle design and treating optimization has high potential in expediting the process of personalized treatment.

Nevertheless, some issues still lie in its nanoparticle biocompatibility, long-term safety, and clinical translation despite its major developments. Nevertheless, progressive research and innovation in the field of nanomedicine and artificial intelligence are still moving us toward the achievement of successful treatment of MDR and better cancer treatment.