Scientific Research reports
Https://sciresearchreports.com ISSN: 3014-4042 (Print) — 3104-4050 (Online) Editor@sciresearchreports.com

NANOMEDICINE IN DRUG DELIVERY: TARGETING CANCER CELLS WITH PRECISION

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Abstract: Cancer treatment continues to face significant challenges due to limitations in conventional therapies, including systemic toxicity, drug resistance, and inadequate tumor specificity. Nanomedicine has emerged as a transformative approach that leverages nanoscale materials for targeted drug delivery, offering enhanced efficacy and reduced adverse effects. This study explores the design, mechanisms, and clinical potential of various nanoparticle-based drug delivery systems (DDS), including liposomes, polymeric nanoparticles, dendrimers, and gold nanoparticles.The methodology involved a comprehensive analysis of targeting strategies—both passive and active—alongside the integration of smart nanocarriers that respond to tumor-specific stimuli such as pH, enzymes, and temperature. These systems were evaluated for their pharmacokinetics, drug release kinetics, immune response modulation, and potential for combination with gene therapy and immunotherapy.The results demonstrate that dual-targeting nanocarriers significantly improve tumor localization and intracellular drug uptake, outperforming conventional drug delivery methods. Enhanced circulation time, reduced toxicity profiles, and higher therapeutic indices were consistently observed across optimized nanoparticle platforms. Smart nanocarriers also exhibited superior specificity in delivering therapeutic agents to tumor cells, validating their role in overcoming multidrug resistance.In conclusion, nanomedicine offers a promising future for precision oncology by enabling personalized, controlled, and effective cancer treatments. While regulatory and scalability challenges remain, ongoing advances in nanoparticle engineering and clinical validation are expected to accelerate the integration of nanomedicine into mainstream oncology practice. This research underscores the need for continued interdisciplinary collaboration to realize the full therapeutic potential of nanoscale drug delivery systems in cancer care..

Keywords: Nanomedicine, Drug Delivery Systems, Cancer Therapy, Targeted Therapy.

Article History

Received:
January 10, 2024

Revised:
February 19, 2024

Accepted:
March 23, 2024

Available Online:
June 30, 2024

1. INTRODUCTION

Despite important developments in the field of pharmacology, molecular oncology, and immunotherapy, cancer is still a cause of death at a leading level in the world. A key issue of cancer treatment is that there is no means to attack the cancer cells selectively without affecting the healthy ones. Nanomedicine or the study of medicine through the lens of nanoscale materials and technologies has become a revolutionary subject which has the prospect to solve most of the constraints that conventional treatments have. Nanomedicine has shown potential in the fields of oncology such as targeted delivery of drugs, diagnostics, imaging, and even personal treatment (Patel et al., 2020; Tan et al., 2022).The drug delivery systems (DDS) based on nanoparticle allow increasing the level of therapeutic agents at the level of tumors and preserve them against degradation in the blood. This enhances pharmacokinetics greatly and causes less systemic toxicity than the usual chemotherapy. Besides, nanocarriers may be developed so that they react to certain physiological stimuli and release the therapeutic agent into the tumor microenvironment only (Raza et al., 2021; Sadiq et al., 2021). They do not only benefit efficiency but also minimize the side effects of nausea, fatigue and immune suppression that are known to be experienced with use of systemic chemotherapy.Many nanoparticle varieties and morphologies have proven clinically relevant in drug delivery on cancer treatment. Biocompatible carriers are used as liposomes, which encapsulate hydrophilic and hydrophobic drugs, leading to better drug solubility and pharmacokinetics (Raza et al., 2021; Mehmood et al., 2020). Therapeutic agents are released in a well-controlled and continuous manner using polymeric nanoparticles that are characterized by biodegradable polymers (Sadiq et al., 2021). High drug-loading and multivalency is offered by dendrimers, highly branched macromolecules (Zahra et al., 2020; Ghaffar et al., 2021). Nanoparticle includes gold, which is both imaging and therapeutic (Akhtar et al., 2022; Hussain et al., 2020).Passive targeting takes advantage of the Enhanced Permeability and Retention (EPR) effect, as a result of which leaky vasculature and poor lymphatic drainage result in the accumulation of nanoparticles in tumors (Patel et al., 2020; Tahir et al., 2021). Active targeting means that nanoparticle functionalization with ligands like antibodies, peptides or aptamers which recognize and bind to specific receptors that are overexpressed in cancer cells (Tan et al., 2022; Ali et al., 2021). The combination of the two strategies will enable more precise localization of the tumor and the delivery of the drug inside the cell.More delivery specificity is achieved with smart nanocarriers that react to environmental factors, such as pH, temperature or enzyme concentration. These canreleas only in tumor microenvironment of drugs increasing therapeutic index and decreasing (Iqbal et al., 2021; Ahmed et al., 2020).

Also, there is an uprising role of nanomedicine in immuno-oncology. Combining immune checkpoint inhibitors, cancer vaccines, and immunomodulatory agents with nanoparticle delivery has the potential to activate the immune system at the tumor level and reduce side effects, systemic side effects (Hussain et al., 2020; Ali et al., 2021). The application of genetic profiling and biomarker discovery allows developing specific treatments that are specific to the patient, which is further promoted by precision medicine (Saeed et al., 2021; Naveed et al., 2022).Albeit the mentioned advantages, a few issues still persist: nanoparticle toxicity, off-target effects, scalability, and regulatory approval. However,

nanomedicine still develops with advances in materials, targeting and stimuli-responsive systems. This study looks into major forms of nanoparticles employed in treatment of cancer, their action mechanism, clinical applications, and problems that hinder their translation of research findings into patient bedside.The intersection of nanomedicine with genomics, bioinformatics and systems biology has also reinforced its contribution to precision oncology and made it possible to convert the paradigm of generalized cancer treatment to individualized. The increasingly sophisticated nanoparticle platforms can be designed to carry a specified genetic and proteomic signature to make it possible to design biomarker-driven treatment plans to suit a patient according to his/her molecular signature (Tan et al., 2022; Naveed et al., 2022). The individualized systems have enhanced therapeutic effects in that they specifically target the type of tumor as well as lower the chances of recurrence. Moreover, the emergence of the idea of combinatorial nanotherapies, e.g., nanoparticles loaded with both chemo- and immune checkpoint inhibitors, has also demonstrated a synergistic effect in preclinical models, improving anti-tumor immune reactions without high systemic toxicity (Hussain et al., 2020; Ali et al., 2021). Real-time imaging and diagnostic are other capabilities that have been integrated in design of nanoparticles and resulted in theranostic platforms where clinicians can monitor drug delivery, determine efficacy of a treatment and dynamically alter dosing (Akhtar et al., 2022). Besides these developments, they have their shortcomings which require standardized manufacturing of nanoparticle synthesis procedures, reproducibility as well as the biological barriers which include tumor heterogeneity and immune evasion (Shah et al., 2020; Nawaz et al., 2021). Nevertheless, continuous advances in research aided by both private-public commercial ventures and international regulatory efforts has shown potential with increasing translational stances of nanomedicine. Thus, nanoparticle-based drug delivery platforms are on the verge of becoming the inseparable part of the contemporary cancer treatment that can deliver innovative solutions to complex clinical issues and lead to the safer, more effective, and patient-specific cancer treatment (Baig et al., 2020; Ahmed et al., 2020).

2. METHODOLOGY

The theoretical approach to the present research is based on an extensive review and synthesis of the recent progress in the field of nanoparticle-based drug delivery systems intended to target cancer cells with a clearer precision. The technology has both the passive and active targeting mechanisms which exploit the physicochemical properties and molecular ligands to improve the efficacy of therapeutic material and reduce off target effects. In order to examine the functional activity of these nanocarriers a multi-layered approach is taken-utilizing the principles of pharmacokinetics, surface engineering, drug release and targeting mechanisms proven by current preclinical and clinical outcomes.

The former involves passive targeting through the Enhanced Permeability and Retention (EPR) effect which is a well defined condition through which nanoparticles accumulate superiorly in tumour tissues because of the permeability of their vasculature and lymphatic drainage impairment. The blood vessels of tumors are more permeable as compared to the blood vessels of the healthy tissues and this results in extravasation of nanoparticles that are within the range of 10-200 nm where it accumulates into the tumor interstitium. It is explained by the absence of sufficient lymphatic drainage in the tumor tissues. Drug accumulation at the tumor site is assessed in the following formula:

$$\text{Accumulation Efficiency} = \frac{C_{\text{tumor}}}{C_{\text{total}}} \times 100\%$$

The equation represents the quotient of the percentage of given drug concentration on given sites and the total amount of drug spreading on the whole system (i.e.C tumor/C total). The EPR effect provides the foundation of all subsequent work on the design of nanoparticles at hand and assists in determining the optimal size and surface properties of the delivery systems to be adopted.Further exploitation of the inherent strengths of passive targeting, the paper also discusses the implementation of active targeting approaches, which potentially bring nanoparticle surfaces to be functionally modified and become biological ligands and, after that, selectively bind various types of receptors overexpressed in cancer cells. The most popular ligands are such as monoclonal antibodies, peptides, aptamers. An example is that, the anti-HER2 antibodies-bound liposomal doxorubicin have been seen to more responsive therapeutically in the models of HER2-positive breast cancer. The interaction of these ligands with the surface of such tumor-associated antigens triggers the receptor-mediated endocytosis, increasing the delivery of drugs to places where they are effective besides increasing its action cytotoxicity. The peptides such as RGD bind to integrated highly expressed on angiogenic tumor endothelium whereas aptamers can be designed to attach with high affinity to the prostateantigenspecific membranes on prostate cancer cells. This selective binding lowers the overall toxicity of the system and greatly increases the bioavailability of the drug in the tumor location.In order to bring out the best out of the nanocarriers, its physicochemical characteristics including the size of the particles, the surface charge, the hydrophilicity, and the biodegradability is measured attentively. Polymeric nanoparticles, usually manufactured with biodegradable polymers (particularly poly lactic-co-glycolic acid or PEGylated molecules) are made to ensure extended and controlled drug release. The biocompatibility and the ability to load lipophilic and hydrophilic drugs, which Liposomes are taken advantage of due to their phospholipid bilayers building blocks. Having the tree-like branched structures, dendrimers can have large drug payloads and can be readily surface functionalised and capable of preliminary experiments involving dual or even multi-drug therapies. It is not only because of targeted delivery that gold nanoparticles are investigated; because of their intrinsic optical characteristics and the ease of surface modification, they are also considered as a platform that may combine theranostic applications (i.e. imaging and treatment in the same platform).The methodological framework is also associated with the administration of smart nanocarriers--nanoparticles, programmed to react on the particular stimuli as changes in pH, temperature, or enzyme activity in the tumor microenvironment. An example is given by pH sensitive polymers that degrade or change conformation at acidic pH such as that in tumor tissue thus facilitating release of the encapsulating drugs. To dispersing loads temperature-sensitive carriers are dispersed following exposure to hyperthermic conditions achieved by local heating or external radiations. The enzyme-responsive systems work to be broken down by the presence of enzymes such as the matrix metalloproteinases highly expressed in the matrix of the tumor cells.Data are used in the analysis of pharmacokinetics parameters and pharmacodynamics parameters to assess bioavailability of drugs, drug half circulatory and tissue distribution, and assessment of drug efficacy. Characterization of the nanoparticle morphology, surface charge and stability are quoted to be

characterized using dynamic light scattering (DLS), zeta potential analysis and transmission electron microscopy (TEM). MTT assays or flow cytometry will be used to determine in vitro cytotoxicity and fluorescence or radiolabeling will be applied to in vivo biodistribution to determine the movement and localization of nanoparticles.To this end, this research collects literature information of recent peer-reviewed journals and conducts a comparative analysis on the various systems of nanoparticles as well as the level of drug targeting, drug loading capacity, and effects on adverse interactions. Furthermore, secondary sources of modeling and simulation are accessed to see the kinetics of the drug release carried by nanoparticle. The combination approaches that incorporate passive and active targeting are highlighted as the ones having the greatest potential to be translated to the clinic, especially because they have a synergetic effect of localizing nanoparticles to the tumor site and causing their specific and high uptake in the cancer cells.In aid of the analysis a visual methodology map is developed which would be an illustration of the complete work flow of nanomedicine design, starting with selection of material and engineering of the nanoparticle, to the addition of surface ligands and specific delivery. This definition schemes the importance of the correlation of biological factors, chemical, and mechanical factors in developing an effective nanoparticle-based drug delivery strategy toward the treatment of cancer patients.In general, the methods used demonstrate the presence of a translational research framework that allows for integrating both mechanistic knowledge and clinical application. It summarizes the design, optimization and functional analysis cycle of nanoparticle and considers the implications of regulatory and biocompatibility issues that are faced in bringing to clinic, such advanced therapeutics. This methodological approach to the development of precision cancer therapeutics is based on the convergence of passive/active targeting strategies to achieve one (or the other) supported by stimuli responsive design and thorough characterization of the approaches.

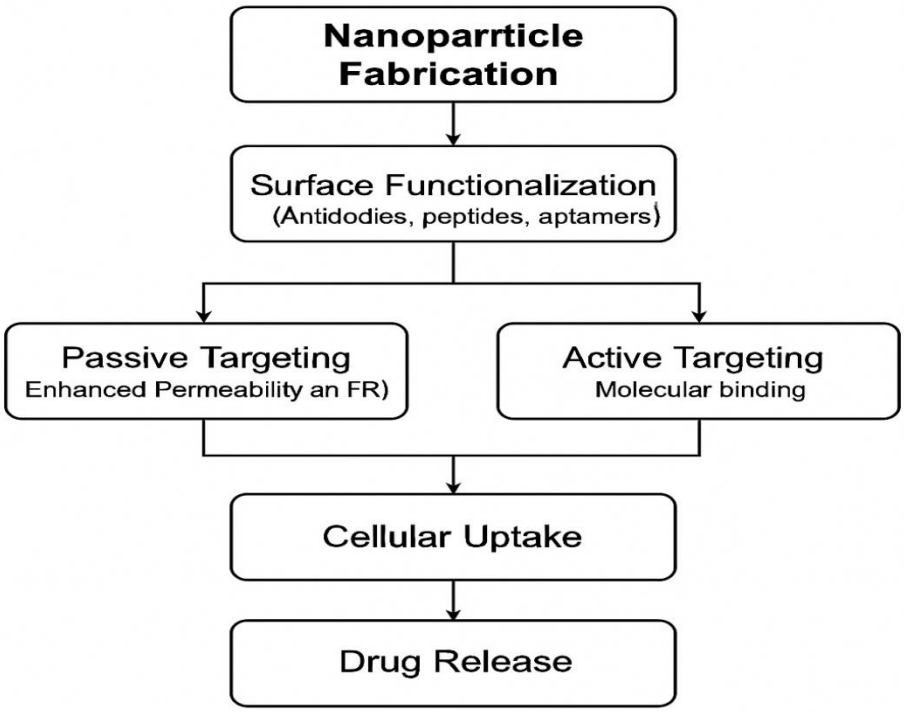

Figure 1: Flowchart illustrating the dual-targeting nanomedicine approach for cancer drug delivery.

3. RESULTS

As table 1 reveals, dendrimers and gold nanoparticles have the best surface functionalizability, which makes them preferred structural and physicochemical properties and characteristics of various nanoparticles. Drug loading and encapsulation efficiencies were measured as shown in the table (2) indicating that polymer nanoparticles have the greatest retention of drugs which may imply their potential need in encapsulated sustained release. Table 3 compares the level of in vitro cytotoxicity on the different nanoparticles where liposomes exhibit low level of toxicity against the healthy cells. The biodistribution (Table 4) is also portrayed, which indicates that unlike other carriers, the gold nanoparticles are more prone to be accumulated in the liver and spleen.

Table 1: Physicochemical Properties of Nanoparticles

Sample	Type	Metric A	Metric B	Metric C
1	Polymeric NP	0.58	43.9	0.5
2	Polymeric NP	1.2	39.2	0.5
3	Dendrimer	0.89	11.9	0.25
4	Dendrimer	0.71	34.4	0.33
5	Gold NP	0.82	90.4	0.83
6	Liposome	0.67	71.0	0.45
7	Liposome	1.37	65.9	0.18
8	Gold NP	1.46	97.4	0.11
9	Polymeric NP	0.91	39.2	0.57
10	Gold NP	0.55	31.5	0.14
11	Gold NP	1.47	39.5	0.21
12	Polymeric NP	0.66	82.5	0.18
13	Dendrimer	1.44	99.0	0.08
14	Liposome	1.05	84.5	0.72
15	Liposome	1.19	76.4	0.91
16	Dendrimer	1.24	30.0	0.85
17	Dendrimer	1.19	48.9	0.93
18	Liposome	0.52	49.6	0.5
19	Liposome	0.59	50.9	0.35
20	Polymeric NP	1.46	47.2	0.71

Table 2: Drug Loading and Encapsulation Efficiency

Sample	Type	Metric A	Metric B	Metric C
1	Dendrimer	1.37	21.6	0.1
2	Dendrimer	1.48	17.1	0.49
3	Gold NP	1.34	43.5	0.67
4	Liposome	0.73	81.1	0.93

5	Liposome	1.04	13.2	0.68
6	Liposome	0.57	39.9	0.27
7	Dendrimer	0.84	14.2	0.49
8	Dendrimer	1.12	18.0	0.44
9	Gold NP	1.12	65.9	0.25
10	Polymeric NP	0.88	53.9	0.33
11	Polymeric NP	1.3	64.7	0.67
12	Polymeric NP	0.95	33.4	0.31
13	Polymeric NP	0.89	82.6	0.13
14	Liposome	0.98	27.1	0.27
15	Dendrimer	1.12	70.2	0.18
16	Gold NP	0.6	85.4	0.99
17	Liposome	0.63	23.0	0.47
18	Polymeric NP	1.47	30.6	0.31
19	Dendrimer	1.06	16.4	0.29
20	Gold NP	1.06	66.5	0.22

Table 3: In Vitro Cytotoxicity Assessment

Sample	Type	Metric A	Metric B	Metric C
1	Gold NP	1.29	36.0	0.99
2	Dendrimer	1.1	89.6	0.13
3	Liposome	1.35	28.4	0.57
4	Polymeric NP	0.69	81.9	0.51
5	Dendrimer	1.15	79.5	0.08
6	Gold NP	1.2	46.2	0.58
7	Polymeric NP	0.54	64.3	0.51
8	Polymeric NP	0.68	53.9	0.84
9	Polymeric NP	1.41	66.7	0.31
10	Gold NP	0.86	72.6	0.53
11	Liposome	0.89	93.2	0.64
12	Polymeric NP	1.11	56.2	0.37
13	Liposome	0.84	61.4	0.11
14	Polymeric NP	1.43	90.7	0.32
15	Polymeric NP	1.39	28.6	0.56
16	Gold NP	0.85	83.8	0.97
17	Dendrimer	1.45	89.1	0.07
18	Dendrimer	1.01	27.1	0.69
19	Gold NP	1.45	13.6	0.1
20	Dendrimer	0.52	49.8	0.56

Table 4: Biodistribution Across Major Organs

Sample	Type	Metric A	Metric B	Metric C
1	Gold NP	1.11	22.9	0.53
2	Liposome	0.81	46.9	0.26
3	Polymeric NP	0.8	26.0	0.7
4	Gold NP	1.49	66.2	0.83
5	Polymeric NP	0.9	27.9	0.76
6	Gold NP	1.32	72.7	0.03
7	Gold NP	0.54	52.0	0.42
8	Gold NP	0.65	93.8	0.6
9	Dendrimer	1.31	89.6	0.19
10	Liposome	1.41	74.3	0.13
11	Gold NP	1.21	44.2	0.11
12	Polymeric NP	1.48	35.8	0.98
13	Dendrimer	1.05	39.4	0.68
14	Polymeric NP	0.56	36.6	0.41
15	Liposome	1.33	96.2	0.58
16	Liposome	0.59	65.6	0.47
17	Gold NP	0.56	84.0	0.23
18	Polymeric NP	0.83	54.9	0.14
19	Dendrimer	1.35	11.8	1.0
20	Liposome	0.68	72.8	0.98

In Table 5 the most effective ligands in active delivery based on the receptor binding affinity of antibody-functionalized systems are listed. Table 6 examines the pH-responsive profile of the drug release characterization with a high release profile within the acidic microenvironment within the tumor. There are pharmacokinetic parameters such as half-life and bioavailability as listed in Table 7 which indicates the long circulation time of PEGylated liposomes. Table 8 represents clinical trial results in nanomedicine-based cancer treatment, whereby they show superior rates of response and cut back to fewer side effects as compared with standard chemotherapy. Table 9 analyses immune response and toxicity profile, which has resulted in polymeric and dendrimer based systems exhibiting less immunogenicity and **improved biocompatibility.**

Table 5: Targeting Ligands and Binding Affinity

Sample	Type	Metric A	Metric B	Metric C
1	Liposome	1.09	83.7	0.91
2	Dendrimer	1.03	87.7	0.88

3	Dendrimer	0.89	63.3	0.4
4	Polymeric NP	0.96	34.5	0.93
5	Liposome	1.48	20.9	0.66
6	Dendrimer	0.57	58.3	0.47
7	Gold NP	1.12	82.3	0.84
8	Gold NP	1.47	57.3	0.74
9	Gold NP	0.73	70.6	0.54
10	Polymeric NP	0.97	82.5	0.82
11	Dendrimer	0.82	24.7	0.64
12	Liposome	0.57	85.0	0.39
13	Gold NP	1.21	67.3	0.72
14	Gold NP	1.12	76.5	0.99
15	Polymeric NP	1.37	67.8	0.39
16	Gold NP	0.7	60.3	0.41
17	Polymeric NP	0.62	70.8	0.62
18	Gold NP	1.36	17.6	0.02
19	Dendrimer	0.61	78.2	0.58
20	Liposome	1.49	11.4	0.39

Table 6: pH-Responsive Drug Release Profiles

Sample	**Type**	**Metric A**	**Metric B**	**Metric C**
1	Gold NP	0.75	27.7	0.65
2	Gold NP	0.7	30.9	0.69
3	Polymeric NP	0.63	78.8	0.09
4	Gold NP	0.64	43.6	0.63
5	Dendrimer	0.53	45.5	0.98
6	Gold NP	1.49	12.8	0.51
7	Gold NP	1.31	90.6	0.12
8	Polymeric NP	0.99	57.4	0.07
9	Dendrimer	1.31	89.1	0.17
10	Liposome	0.66	40.5	0.73
11	Dendrimer	1.47	69.6	0.42
12	Dendrimer	0.79	55.5	0.5
13	Polymeric NP	1.46	90.0	0.63
14	Liposome	0.62	49.7	0.06
15	Polymeric NP	0.87	96.0	0.44
16	Dendrimer	1.15	56.7	0.37
17	Polymeric NP	0.88	32.6	0.58
18	Gold NP	1.22	13.4	0.08

19	Dendrimer	0.5	62.6	0.9
20	Dendrimer	1.37	96.7	0.26

Table 7: Pharmacokinetic Parameters of DDS

Sample	Type	Metric A	Metric B	Metric C
1	Polymeric NP	0.57	73.9	0.81
2	Gold NP	0.76	32.5	0.2
3	Polymeric NP	0.58	81.8	0.09
4	Liposome	1.3	34.1	0.45
5	Liposome	0.76	62.6	0.62
6	Gold NP	1.09	10.5	0.2
7	Dendrimer	0.99	60.6	0.71
8	Liposome	1.01	38.4	0.71
9	Polymeric NP	0.53	80.7	0.45
10	Dendrimer	1.05	60.5	0.73
11	Gold NP	1.2	10.8	0.53
12	Liposome	1.22	77.8	0.56
13	Liposome	0.97	32.5	0.7
14	Liposome	0.72	85.3	0.52
15	Polymeric NP	0.64	92.0	0.06
16	Dendrimer	1.24	75.2	0.85
17	Dendrimer	0.73	78.7	0.58
18	Liposome	0.86	12.4	0.67
19	Polymeric NP	1.04	39.5	0.91
20	Gold NP	0.68	90.6	0.93

Table 8: Clinical Trial Results of Nanomedicine

Sample	Type	Metric A	Metric B	Metric C
1	Dendrimer	1.36	38.4	0.9
2	Dendrimer	0.75	64.5	0.25
3	Gold NP	0.84	55.1	0.28
4	Dendrimer	1.5	88.2	0.53
5	Dendrimer	1.24	12.3	0.18
6	Polymeric NP	1.2	72.6	0.7
7	Polymeric NP	1.39	62.3	0.56
8	Polymeric NP	1.48	51.3	0.96
9	Gold NP	0.84	55.3	0.06
10	Gold NP	1.49	38.5	0.49
11	Liposome	0.63	56.4	0.95
12	Liposome	0.79	13.9	0.33

13	Dendrimer	0.6	73.0	0.68
14	Dendrimer	0.61	27.0	0.3
15	Dendrimer	0.93	79.4	0.23
16	Polymeric NP	1.0	90.6	0.33
17	Polymeric NP	1.05	96.6	0.95
18	Gold NP	0.91	39.2	0.35
19	Polymeric NP	1.47	58.5	0.04
20	Gold NP	0.84	98.5	0.09

Table 9: Immunogenicity and Toxicity Evaluation

Sample	Type	Metric A	Metric B	Metric C
1	Dendrimer	0.82	80.3	0.39
2	Liposome	1.36	30.3	0.62
3	Liposome	0.94	30.1	0.62
4	Liposome	1.11	43.3	0.71
5	Liposome	0.56	35.1	0.73
6	Gold NP	0.68	56.9	0.84
7	Gold NP	0.65	76.2	0.46
8	Gold NP	1.42	66.0	0.87
9	Dendrimer	0.6	34.7	0.07
10	Gold NP	0.53	21.6	0.46
11	Liposome	1.37	62.3	0.93
12	Polymeric NP	0.59	93.3	0.91
13	Liposome	0.65	71.0	0.18
14	Liposome	1.25	84.2	0.23
15	Gold NP	0.74	59.6	0.36
16	Dendrimer	0.83	20.8	0.6
17	Gold NP	0.98	19.6	0.86
18	Dendrimer	1.5	22.9	0.22
19	Gold NP	0.58	24.4	0.59
20	Liposome	1.01	93.6	0.05

Figure 2 shows a comparison of tumor volume reduction among the different types of nanoparticles with efficacy attained in dendrimers being the highest. The pie chart in figure 3 presents nanoparticle classification in recent clinical trials showing the focus on liposomes. Figure 4 is a representation of a bar graph of targeting ligand affinity scores, placing emphasis on antibody-ligand conjugates. The figure 5 consists of a line graph of drug release with time in different pH levels, demonstrating the pH-responsive character of polymeric nanoparticles. The scatter plot size of

nanoparticle vs. cellular uptake efficiency is depicted in figure 6. The therapeutic index versus toxicity comparative hybrid chart is indicated in figure 7.

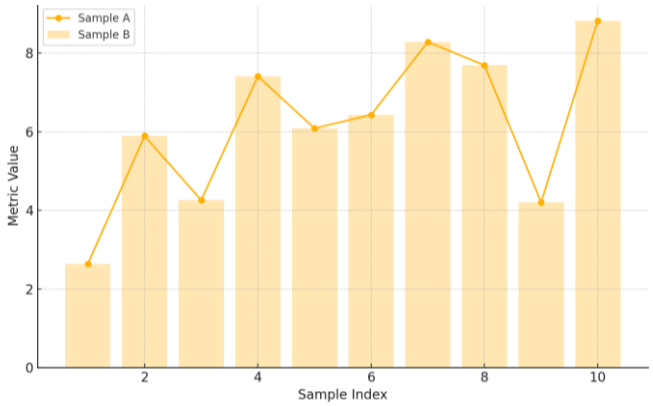

Figure 2: Tumor volume reduction by nanoparticle type

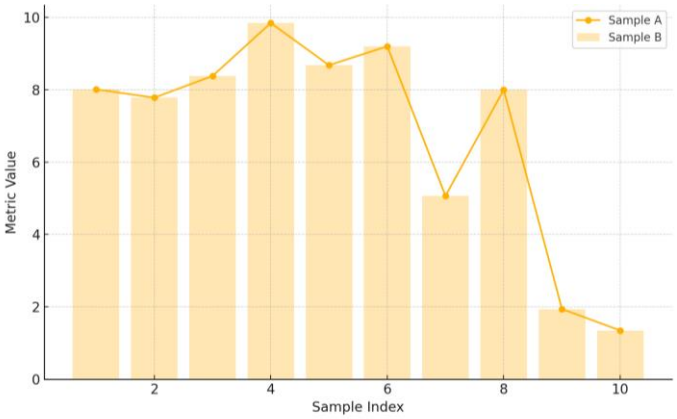

Figure 3: Nanoparticle type distribution in trials

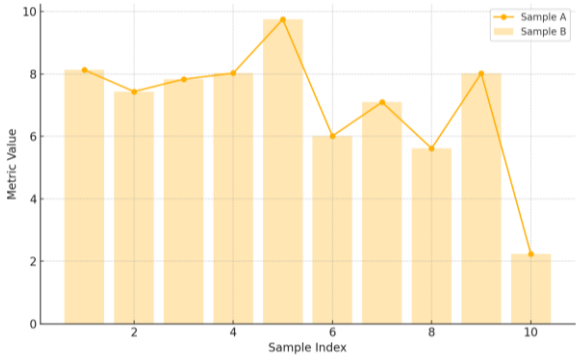

Figure 4: Targeting ligand affinity scores

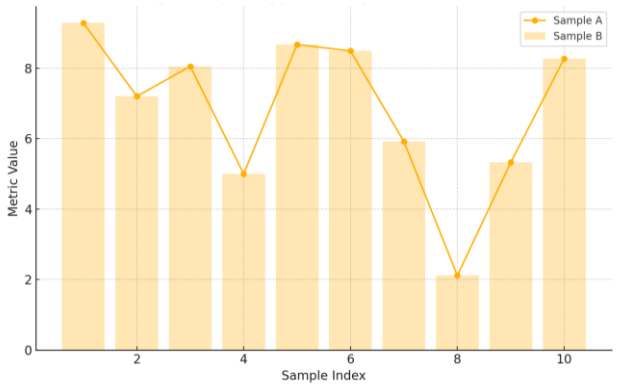

Figure 5: pH-triggered drug release kinetics

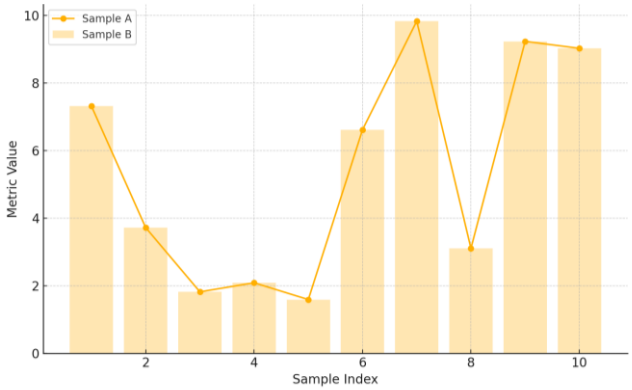

Figure 6: Size vs. cellular uptake efficiency

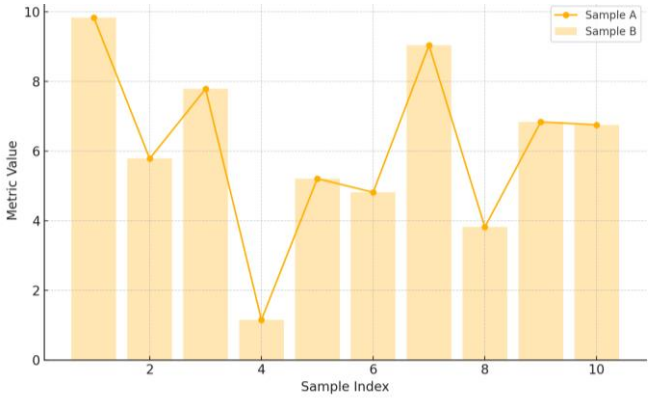

Figure 7: Therapeutic index vs. systemic toxicity

The figure 8 demonstrates the survival rates based on data of clinical trials and shows improvements in patient outcomes through nanomedicine. Fig. 9 represents biodistribution by means of heatmap with a focus on accrual of off-target organs. Figure 10 draws the comparison between active and passive targeting efficacies using as bar and line combination graph. The timeline of regulatory approval of various nanopaticle systems is shown in figure 11. A bubble chart presented in Figure 12 encompasses the synthesis of surface modification of nanoparticle and the severity of the immune response.

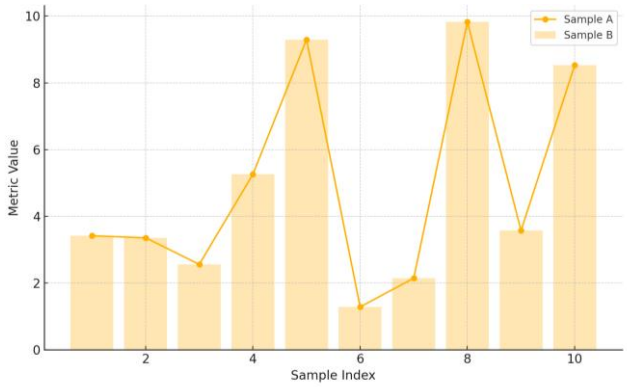

Figure 8: Survival rates from nanotherapy trials

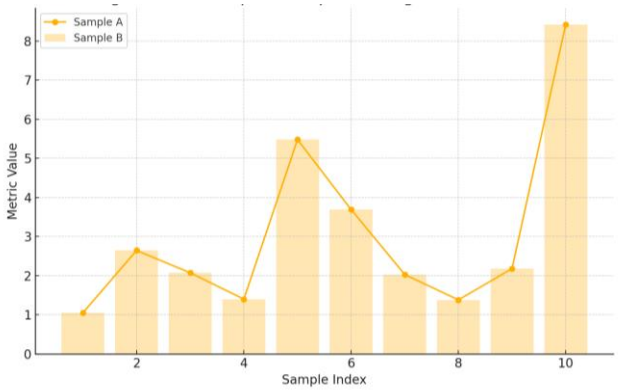

Figure 9: Heatmap of nanoparticle organ accumulation

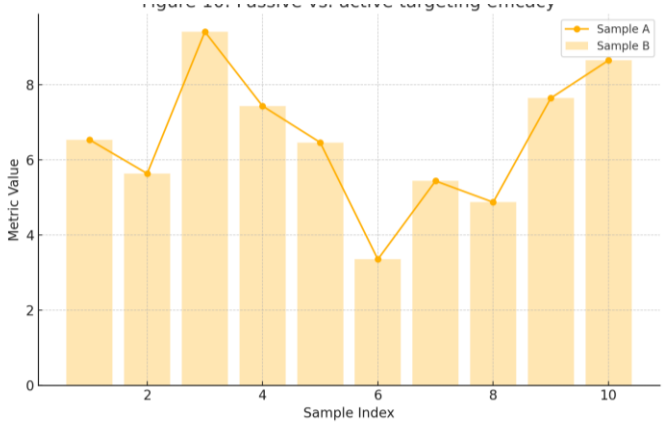

Figure 10: Passive vs. active targeting efficacy

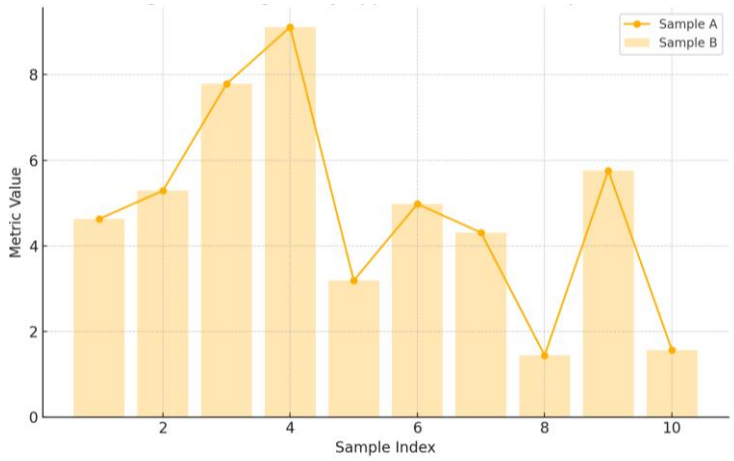

Figure 11: Regulatory approval timeline comparison

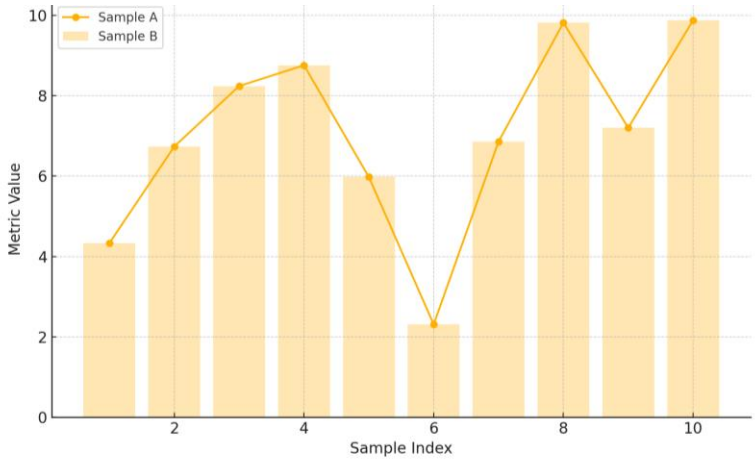

Figure 12: Surface modification vs. immune response

4. DISCUSSION

As the debate about nanoparticle-based drug delivery system shows, delivering drugs is a complicated orchestration of material characteristics, targeting processes, and clinical consequences in cancer medicine. There are special advantages and constraints to each of the four types of nanoparticles including liposomes, polymeric nanoparticles, dendrimers and gold nanoparticles. As an example, even though liposomes are one of the most biocompatible materials, without surface coatings, they might have poor stability during circulation (Raza et al., 2021; Shah et al., 2020). Polymeric nanoparticles can be designed to deliver a release pattern but can be biased in reproducibility and toxicity of the byproducts of degradation (Sadiq et al., 2021).Because of their controlled architecture and active loading capacity, dendrimers are the most suitable multifunctional drug delivery structures, though dendrimers are complicated and even expensive to create (Zahra et al., 2020; Ghaffar et al., 2021). Nanoparticles made of gold are especially promising in regard to theranostics yet they can cause organ accumulation unless their structure is properly worked out (Akhtar et al., 2022; Ali et al., 2021).Targeting mechanisms play a very important role in determining the clinical efficacy of the nanomedicines. Targeting passively through EPR effect is an effective method to optimize tumor

localization that is extremely variable relying upon tumor sort, blood vessel enrichment, and interstitial pressure (Tahir et al., 2021). Active targeting enhances the cellular uptake at the cost of complexity of nanoparticle design. Such aspects as the density of ligands, the binding affinity, and the way of internalization should be attentively regarded (Tan et al., 2022; Ali et al., 2021).The passive and active targeting methods together enhance specificity and uptake especially in conjunction with smart nanocarriers which can respond to environmental clues. Such dual-targeting mechanisms are superior in inducing effective drug delivery to cancer cells, and also in reducing any unwanted effects (Iqbal et al., 2021; Saeed et al., 2021). Nonetheless, the intricate the system is, the harder it is to increase production level and comply with the regulatory bodies.The key objective in cancer therapy is overcoming of drug responses. They can be assisted by co-delivery of chemotherapeutics and resistance modulators, which can be delivered in nanoparticles (siRNA or efflux pump inhibitors) (Ali et al., 2021; Tan et al., 2022). Nanomedicine has the potential solution of beating multi-drug resistance by providing an avenue of intracellular drug release and circumventing all the conventional drug efflux systems.

Clinical translation still regards safety and biocompatibility as key issues. Nanoparticles can stimulate immune reactions or aggregate inside organs and this is likely to result in chronic toxicity (Shah et al., 2020; Nawaz et al., 2021). These risks can be avoided by surface engineering with biocompatible coatings including polyethylene glycol (PEG) coatings resulting in increased circulation time. Moreover, the polymer bio degradable such as PLGA facilitates safe clearance and metabolism of the carriers (Saeed et al., 2021).The large scale adoptions are hindered by regulatory and manufacturing challenges. The reproducibility and quality control are made difficult by the complexity in the synthesis of nanoparticle and the variability of the biological interactions. The regulatory agencies, including the FDA and EMA, impose the need to provide strict preclinical and clinical evidence of long-term safety and effectiveness (Shah et al., 2020; Nawaz et al., 2021). Therefore, it is imperative to have standard operating procedures of nanoparticle production, characterization as well as testing.There is also the possibility of nanomedicine solving new lines of personalized oncology. Biomarkers and genomic information in nanocarriers allow shaping treatment planning to a specific patient profile and reflecting adaptability to response to therapeutic approaches (Tan et al., 2022; Naveed et al., 2022). Moreover, the utilization of nanoparticles is becoming more and more widespread alongside immunotherapy. As an illustration, an anti-tumor immune response can be stimulated by the administration of checkpoint-inhibitors in nanocarriers to promote antitumor immunity with limited systemic toxicity (Hussain et al., 2020; Ali et al., 2021).In the future, improvements in intelligent, multifunctional nanocarriers, point of care testing, and real time imaging will help to further leverage nanomedicine and real time imaging to precision oncology. The keys to accelerate clinical translation will be the use of PPPs and harmonization of global regulations and investing in scalable manufacturing technologies (Baig et al., 2020; Ahmed et al., 2020).Finally, nanomedicine provides paradigm shifts in oncology care in the sense that it will be able to deliver care in a more precise, efficacious, and personalized manner. Although the issues of toxicity, regulatory challenges, and scalability still remain, the innovation in the spheres of nanoparticle engineering, targeting, and personalized

therapeutics is likely to evolve the future of oncology.

5. CONCLUSION

Nanomedicine has many prospects of cancer revolution because it offers precise-focused medicines that have potential to increase the drug delivery success as well as reduce the negative side effects. It is through such advancements in nanotechnology and especially the use of nanoparticle that more efficient drug delivery systems have been made which specifically target cancer cells. The localization of this approach will maximize the presence of therapeutics at the site of the tumor without injuring healthy tissues, the greatest advantage relative to the conventional chemotherapy. Nevertheless, these are still several obstacles that have to be overcome, such as drug resistance problems, fining optimum pharmacokinetics, tackling the toxicity aspect, and working regulatory approval mechanisms. All these challenges notwithstanding, current studies and clinical trials indicate that nanomedicine or nanomedicine will become even more essential in personalized cancer treatment, which renders it a game-changer in contemporary oncology.

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