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Modern Strategies in Oncology: A Multidisciplinary Review of Innovative Cancer Therapies

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ABSTRACT

Cancer is a leading cause of death worldwide. Traditional therapies like radiation and chemotherapy often cause severe side effects and still fail to cure many patients, leaving them with few options. Therefore, new, more precise and effective treatments are essential. In recent years, cancer therapy has improved significantly. For example, immunotherapies have been developed to help the immune system attack tumours, targeted drugs can attack specific genetic mutations in cancer cells, and new gene- or cell-based approaches such as CAR-T cell therapy have emerged. Researchers are also using artificial intelligence (AI) to improve cancer diagnosis, predict patient responses to treatments, and speed up drug discovery. At the same time, nanotechnology is playing a growing role in creating better systems for delivering cancer drugs directly to tumours. Looking ahead, research will focus on modifying the tumour microenvironment and understanding how the body's microbiome affects cancer. Another promising strategy is to combine different therapies – for example, giving immunotherapy together with radiation – to improve outcomes. However, many challenges remain: tumours can develop resistance to treatment, therapies can have harmful side effects, and the newest treatments are often very expensive or hard for patients to access. Continued research and global collaboration are needed to overcome these obstacles. With sustained innovation and cooperation, future cancer care has the potential to become much more personalised, less toxic, and ultimately more effective for patients around the world

Keywords: *Targeted therapy; Gene and cell-based therapy; CAR-T cells; Tumour microenvironment; Artificial intelligence; Nanotechnology; Microbiome-cancer axis; Precision oncology*

1. INTRODUCTION

Cancer remains one of the leading causes of death globally, affecting millions of people each year. Due to its complicated nature, it still presents a significant challenge to modern medicine even after years of research. Primarily, cancer develops when normal cells in the body experience abnormal mutations that allow them to proliferate out of control and evade regular impulses that direct cells to stop proliferating or to die. Carcinogenesis describes the series of steps by which healthy cells develop malignant traits. It is caused by an accumulation of genetic and molecular changes that interact with regular regulatory systems *(Stratton et al., 2009)*. Genetic mutation is one of the main factors influencing this process. These mutations can block tumour suppressor genes, which generally control cell division, or stimulate specific genes, which promote cell development. Over time, these changes may lead to the development of tumours. These changes can be caused by various factors, including radiation, infections, inherited gene mutations, and environmental chemical exposure *(Senga et al., 2021)*.

The Hallmarks of Cancer framework was developed by researchers to understand the mechanisms of cancer. These cancer hallmarks, first listed by Hanahan and Weinberg in 2000 and modified in 2011, point out the fundamental attributes that cancer cells tend to acquire in the process of their development. Among these, they can penetrate various types of tissues, resist cell death, avoid being destroyed by immunological systems and possess sustained proportions of growth signalling (*Hanahan et al., 2011*). The impact of the nervous system and microbes on the development of cancer has recently been offered by investigators as new hallmarks (*Senga et al., 2021*). Notwithstanding tremendous cancer care developments, conventional methods of treatments such as surgery, chemotherapy and radiation treatment have experienced wide limitations. Although such strategies have enhanced rates of survival, they carry grave deficiencies which affect both efficacy and quality of life (*Koirala & DiPaola, 2024*). Solid tumour surgery is a mainstay for the management of solid tumours, but is only truly effective for localised disease. Total elimination of the tumour becomes difficult with metastasis or if the tumours hide in anatomically complex regions. Even after apparent successful operation, microscopic cancer cells may be present, and their proliferation will lay the foundation for a recurrence (*Wang et al., 2020*). The general approach to chemotherapy is presumably its main lapse. It affects healthy tissues as well as malignant cells since it indiscriminately affects fast-dividing body's cells. That is why the all too familiar side effects are explained: hair and subsequent loss, weakened immunity, and crippling nausea (*Eslami et al., 2024*). Making the challenge worse are uneven distribution of drugs in tumours, especially those poor in blood or oxygen-deprived (*Koirala & DiPaola, 2024*). Although radiation therapy is not as indiscriminate as chemotherapy, it is equally destructive to adjacent tissues. This so-called collateral damage can develop into fibrosis, poor functioning of the affected organ, and even new cancers decades later (*Rezayatmand et al., 2022*). Even though surgery, chemotherapy, and radiation are fundamental and although their contraindications point to the need for more precise, personalised approaches, it is urgent. Emerging therapies like immunotherapy, targeted drugs, and genetic techniques promise greater specificity with fewer side effects *(Eslami et al., 2024).* This evolution toward precision medicine may finally address the gaps left by traditional treatments, offering hope for more durable remissions and potential cures. Perhaps most concerning is how traditional treatments often fail against cancer stem cells. These resilient cells can withstand therapy, then regenerate tumours afterwards, driving relapse and metastasis. They employ multiple defence mechanisms, from pumping out drugs to repairing DNA damage more efficiently than regular cells *(Rezayatmand et al., 2022).*

New therapies such as immunotherapy and targeted drugs, and genetic techniques are promising better specificity and fewer side effects (*Eslami et al., 2024*). This advance toward precision medicine could, at last, close the gaps left by conventional treatments with hope for longer remissions and potential cures. Most worrying is the way that conventional therapies commonly fail against cancer stem cells. These tough cells are resistant to therapy, regrow tumours again upon completion of therapy, leading to relapse and metastasis. They use various defence mechanisms, from excretion of drugs to fix DNA damage better than normal cells (*Rezayatmand et al., 2022*).

The tumour's local environment makes treatment even more difficult. This complicated network of fibroblasts, immune cells and structural proteins creates protective niches which protect cancer cells (*Koirala & DiPaola, 2024*). Low oxygen content in tumors can also daimthe effect of radiation and some chemotherapies (*Wang et al., 2020*). Personalised medicine is a better alternative to this since it provides treatment planning to reflect the individual characteristics of each cancer of a patient. This strategy employs genetic testing and biomarkers, as well as upgraded diagnostic devices, to make superior treatment choices, improving effectiveness and decreasing side effects. For instance, artificial intelligence (AI) now assists doctors in reading complicated patient data that can be used for writing personalised treatment programs and forecasting outcomes more accurately (*Schürch et al., 2024*). New treatment alternatives have also demonstrated excellent promise as alternatives to conventional therapies. Immunotherapy, particularly checkpoint inhibitors such as dostarlimab, has been spectacularly effective in some cancers with particular defects, and some patients can thus avoid surgery and live a good quality of life (*Alkholifi & Alsaffar, 2022*). Further, the use of nanotechnology has developed new drug delivery means that make chemotherapy more specific and efficient, without the overall body toxicity and for the greater benefit of patient outcomes (*Sanchez-Moreno et al., 2024*). Although such progress has been achieved, the process of implementing personalised and innovative cancer treatments on a large scale is persistently complicated by several obstacles. They include high cost, low access to sophisticated testing and the lack of sufficient clinical studies to support new treatments. Geographical healthcare inequalities among regions and countries also complicate the ability for personalised medicine to reach patients, especially in poorer countries (*Dey et al., 2023*). This review discusses the current situation with personalised and innovative approaches to cancer management to understand what the science is about them, and how they may redefine cancer therapy

2. TARGETED THERAPIES

Selective drugs, in turn, are aimed at specific biochemical pathways in which cancer evolves. As such, targeted drugs are one of the emerging trends in oncology. Specific cancer tissue-targeted therapies spare normal tissues by acting on molecular defects unique to cancer cells, as opposed to the standard chemotherapies that target rapid cell multipliers. Cancer biology understanding on the molecular level creates an opening for the creation of targeted therapies. For instance imatinib, a tyrosine kinase inhibitor, which selectively inhibits, this abnormal protein, was obtained after the discovery of the BCR-ABL fusion gene in the chronic leukaemia caused by the myeloid cells with remarkable improvements in clinical outcomes (Dru In the same way, trastuzumab, which is a monoclonal antibody against HER2 receptor and which prevents growth of tumour has successfully been used to target into HER2 over expression in some breast tumours (*Slamon et al., 2001*).

Advances in genomic technology have made it simpler to achieve the detection of a vast library of molecular targets in various forms of cancer. For instance, there are inhibitors of EGFR like gefitinib and erlotinib, which have been shown to target the EGFR gene mutations in non-small cell lung cancer and show a positive patient outcome (*Lynch et al., 2004*). In turn, ALK inhibitors (a class of anti-cancer drugs acting against the anaplastic lymphoma kinase (ALK) protein) such as crizotinib have been designed because of the discovery of ALK gene rearrangements and patients with ALK. Despite the achievements, several challenges, among them tumour heterogeneity and drug resistance, persist. The resistance mechanism might be phenotypic, the awakening of other signalling pathways, or secondary changes to the target protein. Combination therapies and the next-generation inhibitors are being studied to support overcoming these challenges (*Holohan et al., 2013*). Offering the potential for more efficient and less toxic therapeutic alternatives, targeted therapies represent a significant shift toward individualised medicine in cancer treatment. These therapies provide opportunities for more effective and less harmful treatment options. Clinical studies and ongoing research continually expand the list of molecular targets and refine treatment strategies.

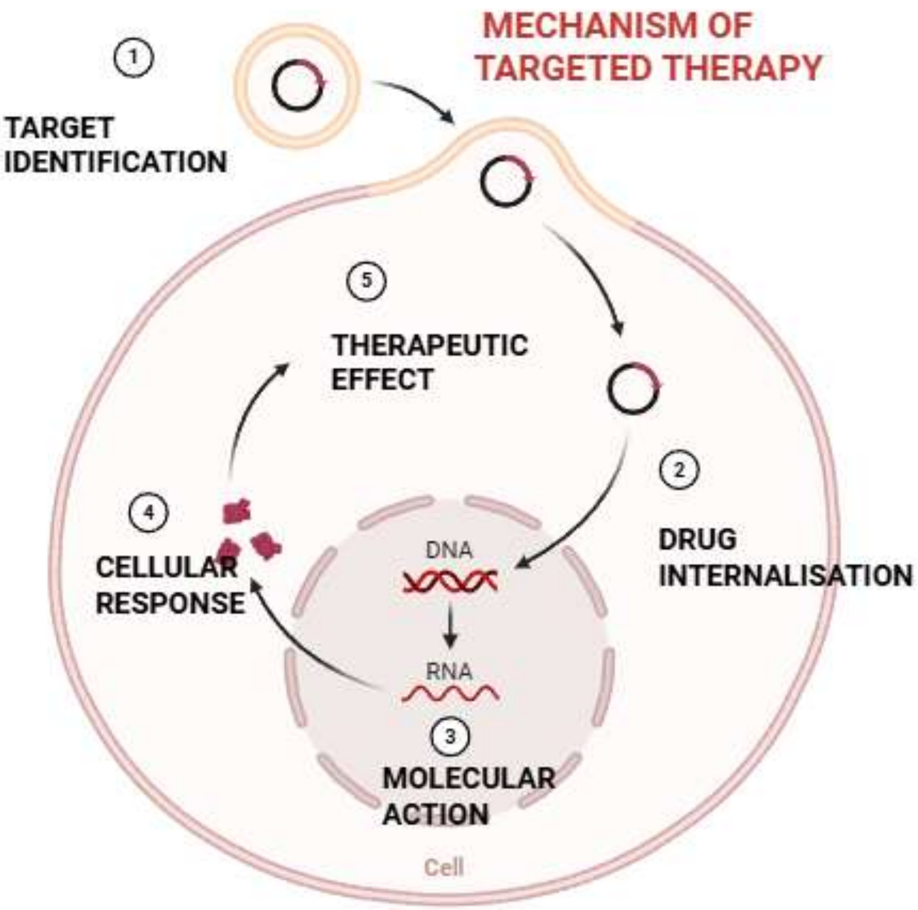

Figure 1: Mechanism of targeted therapy

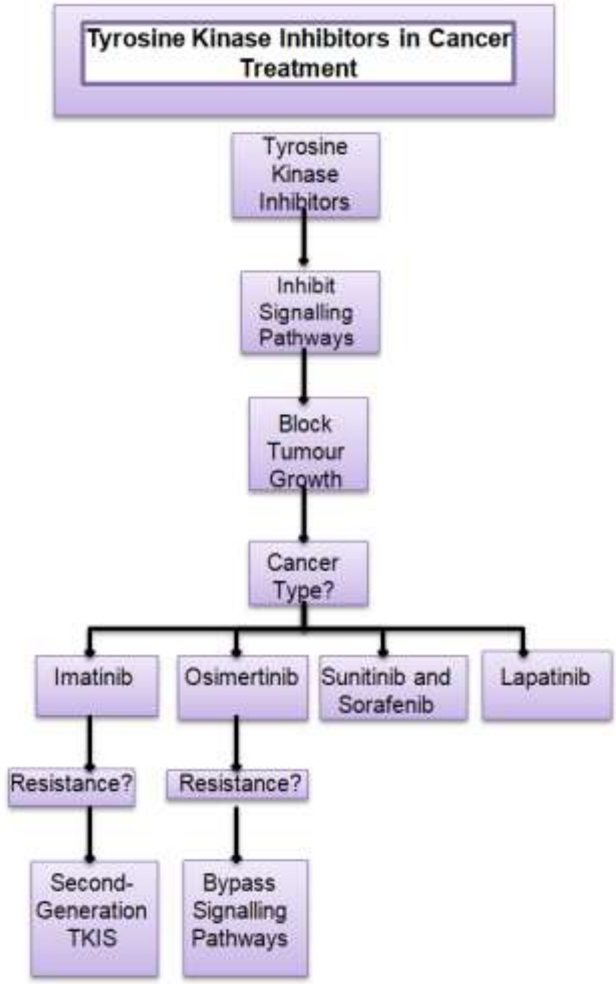

Fig 2: Pathway of Tyrosine kinase inhibitors

2.1 Tyrosine Kinase Inhibitors (TKIS)

Tyrosine kinase inhibitors (TKIS) have developed as an important improvement in targeted cancer therapy. These enzymes block the signalling pathways that control cell growth, survival and proliferation. Changes in such kinases may speed up cancer. TKIS targets IPEC/JF1 cells by blocking signal transduction through binding to the ATP binding site on tyrosine kinases, thereby inhibiting tumour development (*Wu et al., 2011*). Different TKIS target other tumours, and imatinib becomes a major player, especially in targeting the BCR-ABL fusion protein that accounts for the generation of chronic myeloid leukaemia (CML). This enhances survival rates, especially in the chronic domain of CML. The imatinib resistance may come from mutations in the BCR-ABL kinase domain, causing the development of second-generation TKIs such as dasatinib and nilotinib (*Sacha et al., 2014*).

For non-small cell lung cancer (NSCLC), the third-generation TKI for patients with EGFR mutations that show resistance to erlotinib, like first-generation agents, is osimertinib. A critical, phase 3 study (FLAURA trial) showed that patients receiving osimertinib obtained an overall survival rate of 38.6 months while receiving a favourable safety profile, exceeding 31.8 months when compared to other standard TKIS (*Ramalingam Leonetti et al., 2019*). Osimertinib resistance, however, is a possibility because of bypass signalling, i.e. MET or HER2 amplifications (*Tang et al., 2018*). A Brazilian study reported better median overall survival and progression-free survival from EGFR-mutated NSCLC after using erlotinib and gefitinib than conventional chemotherapy in advanced EGFR-mutated NSCLC (*Hung et al., 2024*). As well, a New Zealand study of 752 patients had shorter treatment lengths and greater survival rates (*Aye et al., 2025*)

A case report by Sato et al. (2025) involved the simultaneous treatment of a patient suffering from metastatic renal cell carcinoma and CML with both sunitinib and sorafenib. The monitoring showed constant blood levels with little pharmacokinetic interactions. Despite some side effects, dose changes led to complete cytogenetic response on day 154. In addition, LAPATINIB, a dual EGFR/HER2 TKI, is used in HER-2 positive breast cancer. A phase III study revealed superior survival from a novel antibody-drug conjugate compared to the current treatment with lapatinib and Capecitabine, potentially making it an effective destination option for patients resistant to previous HER2-targeted therapies (*Hu et al., 2024*)

2.2 Monoclonal Antibodies: EGFR and HER2-Targeted Therapies

The killing of tumour cells by species-specific binding to antigens on tumour cells has revolutionised the treatment of cancer, where the mAbs can provide direct death of tumour cells, or an opening for the immune system to target. The evolution of the discipline of biotechnology allows mAbs production in a hybrid, humanised, and fully human systems, which amplify functions and attenuates immunogenicity. Such antibodies may be sent alone, in synergistic groups with common treatment, like radiation and chemotherapy, or be used as transporters for cytotoxic agents right to tumours (*Shahi et al., 2025*).

Critically, in oncology, molecules of the antibody perform HIT of overexpressed proteins by tumour cells, including the human epidermal growth factor receptor 2 (HER2) and the epidermal growth factor receptor (EGFR). These receptors are important in cell division and growth (*Zhu et al., 2024*). mAbs can inhibit the signal for tumour growth, induce apo, yet have therapeutic effects, including recruitment of immune effector functions such as antibody-dependent cellular cytotoxicity (ADCC) and complement-dependent cytotoxicity (CDC) *(Pandit et al., 2025).* Leading mAbs against EGFR & HER2, including cetuximab, panitumumab, trastuzumab and pertuzumab, are clinically useful with excellent response in colorectal, lung & breast cancer. Therapy resistance, though, is still a problem, occurring as secondary mutations or as a result of alternative signalling pathway activation. This throws light on the need for composites and new synthesis of antibodies (*Pandit et al, 2025*).

The new studies have suggested combination therapies like HER2-targeted mAbs associated with chemotherapy and tyrosine kinase inhibitors TKIS) can improve the efficacy of treatment and overcome resistance. Chimeric antigen receptor T-cell (CAR-T) therapy is also coming forth as a desirable approach to HER2-expressing tumours (*Shao et al., 2025*). In addition, clues to the common signalling pathways of EGFR and HER2 indicate that they can provide massive improvements in cancer treatment if both are targeted. The treatment scene for lung HER2-positive cancers is changing with mAbs and TKIS coming to the fore as effective therapies, with still resistance issues (*Reinhorn et al, 2025*).

2.3 PARP Inhibitors

Poly (ADP-ribose) polymerase (PARP) inhibitors act as an important progress in cancer treatment, especially for such types of cancer as BRCA1 /BRCA2 mutation cancers, as is observed in breast cancer. The drugs prevent cancer cells from repairing damaged DNA. From a perspective of synthetic lethality, cells with these mutations already have impaired repair mechanisms, blocking PARP, resulting in the accumulation of DNA damage and cell death.

PARP inhibitors examples include olaparib, niraparib, and Rucaparib used for treating ovarian, breast, prostate and pancreatic cancers. Some of the cancer cells, though, are capable of developing resistance against these drugs, therefore making them less effective in the long run (*Zhu and Shi, 2025*). Researchers are now testing PARP inhibitor combinations with other DNA repair pathways treatments, such as ATR and CHK1 inhibitors, and immune checkpoint inhibitors to stimulate the immune response against tumours (*Drew et al., 2024; Jain et al., 2025*).

The problems presented by the resistance to the PARP inhibitors are, however, very serious. A recent study in pancreatic cancer, conventionally known to have limited therapeutic alternatives, established that various enantiomeric forms of certain molecules have the potential to increase efficacy and lead to resistance overcomes while promoting the potential of refined molecular design in improving treatments of PARP inhibitors (*Khalizieva et al., 2025*).

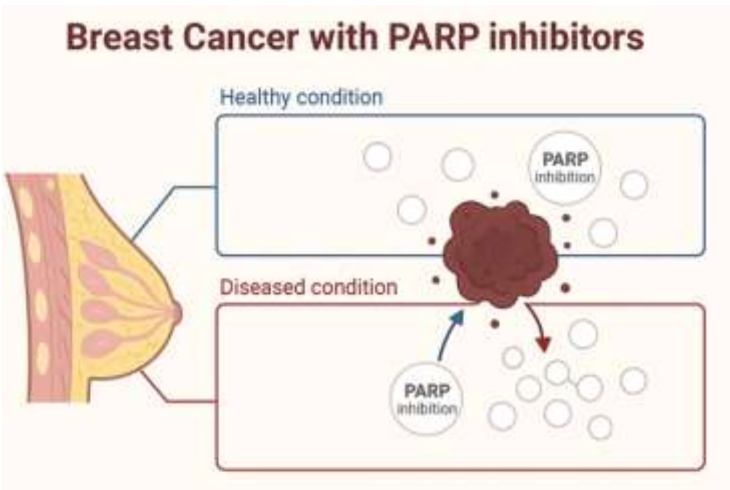

Fig 3: PARP Inhibition

2.4 Advantages and Limitations of Targeted Cancer Therapy

Over the last few years, there have been significant developments in systems of drug delivery that have facilitated the development of targeted cancer therapies by allowing the direct delivery of therapeutic agents into tumour areas, thereby preventing systemic toxicity and limiting toxicity to healthy tissues (*Reddy & Reddy, 2025*) Such contemporary systems also increase drug stability and bioavailability which permits to achieve prolonged and sustained release with a controlled flow, which improves treatment outcomes. Innovations, such as nanoparticles and liposomes, enhance co-delivery of more than one drug, playing an advocating role in combination therapies for counteracting drug resistance.

However, there are serious obstacles to be overcome, such as intricate manufacturing processes, production costs, and large-scale commercialisation (Reddy & Reddy,2025). In addition to these biological barriers, the systems show several weaknesses: among them, the clearance by the immune system and insufficient penetration of the tumour. Therefore, despite the hopes that targeted drug delivery raises, it will require further research to overcome these limitations and make it a better resource in clinical oncology.

Moreover, new opportunities for targeted therapy have arisen from recent progress in nanoparticle-based systems, especially in antibody-drug conjugates (ADCS). These novel systems can especially target cytotoxic agents to cancer cells with improved therapeutic efficiency and reduced normal tissue toxicity (*Abdelhamid et al., 2025*). Besides, they provide controlled drug release and enhance the solubility of hydrophobic drugs, providing potential means of resistance to multidrug.

3. IMMUNOTHERAPY

Immunotherapy leverages the body’s immune system to combat cancer by helping it recognise and attack tumour cells that usually evade detection. Key strategies include immune checkpoint inhibitors, cancer vaccines, adoptive cell transfer therapies, and monoclonal antibodies, which enhance immune responses against malignancies. For example, anti-PD-1 and anti-CTLA-4 antibodies activate immune cells to target cancer *(Gaikwad and Kharat, 2025).* Recent studies highlight the role of inflammation-induced cell death, such as pyroptosis, necroptosis, and ferroptosis, in improving immunotherapy outcomes by making tumours more detectable *(Fu et al., 2024).*

Nanotechnology is revolutionising immunotherapy by enabling precise delivery of tumour antigens and adjuvants, enhancing immune responses while protecting vaccine components from degradation. This technology addresses challenges like manufacturing and regulatory approval *(Delgado-Almenta et al., 2025).* Notable advancements include immune checkpoint inhibitors like ipilimumab, which improved survival in metastatic melanoma *(Hodi et al., 2010*), and PD-1 inhibitors such as pembrolizumab and nivolumab, effective against various cancers *(Motzer et al., 2019).*

3.1 Immune Checkpoint Inhibitors

Immune checkpoint inhibitors (ICIS) have come in to greatly revolutionise cancer treatment, according to the body's immune system to fight tumours. Despite that, a drug resistance to these treatments has emerged in some patients, particularly in lung cancer, where hypoxia, i.e. the lack of oxygen supply to the tumour microenvironment, is important. Hypoxic conditions enable tumours to reprogram immune responses with reduced infiltration and function of anti-tumour T-cells. In addition, hypoxic conditions promote immunosuppressive factors. This adaptation has interfered with therapeutic strategies for the PD-1/PD-L1 pathways, and hypoxia-based mechanisms could be employed to enhance the long-term efficacy of ICIS (*Robles-Oteíza et al., 2024*)

ICIS, in particular PD–1 and PD–L1 inhibitors, have been useful for non–small cell lung cancer (NSCLC). Scientists are coming up with ways of overcoming resistance by including other checkpoints, such as TIGIT, LAG-3, as well as TIM-3, that control immune response. Combination treatments involving PD-1 blockade, this alternative target has shown positive results in clinical trials (*Roussot et al., 2024*). Additionally, studies demonstrate that ICIS could be beneficial for aged patients with advanced NSCLC. According to a systematic meta-analysis by Yao et al, PD-1 and PD-L1 inhibitors can provide superior survival rates in older patients, with similar toxicities observed in younger patients. Age should not be a limit for ICI treatment. Older patients show the same RFS and OS figures (*Yao et al., 2025*).

Tumour mutational burden (TMB) has also arisen as one of the key biomarkers for predicting responses to ICIS in NSCLC. Recent findings show that higher levels of TMB are associated with favourable results after ICI therapy, as a large number of mutations create neoantigens that help the immune system identify and destroy cancer cells. TMB is better considered as a continuum rather than a definite cut-off boundary point with an association with treatment responses (*Yao et al., 2025*). Advancements are also reported in the integration of ICIS targeting PD-1/PD-L1 with CTLA-4 inhibitors, with enhanced results for advanced NSCLC patients. (*Zhao et al. 2025*) Conducting a systematic review found that this combination therapy enhances survival rates through the activation of targeting disparate immune mechanisms. T-cell functioning is recovered within the tumour microenvironment by PD-1/PD-L1 inhibitors, whereas CTLA-4 inhibitors increase the early T-cell activation, contributing to the enhanced systemic anti-tumour immune response.

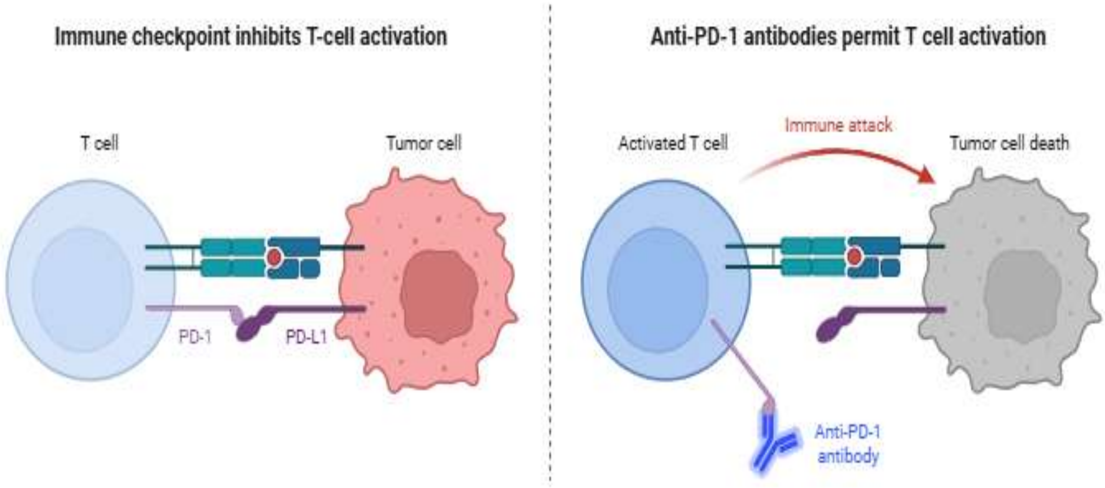

Fig 4: Immune checkpoint inhibitors activating cancer

3.2 CAR T-Cell Therapy

CAR T-cell therapy is an immunotherapy that alters the patients' T cells to attack cancerous cells, causing their cells to express such Chimeric antigen receptors (CARs), such as the CD19. The patient's T-cells are collected, processed in the lab, and injected back into the patient. This therapy is demonstrating promising advancements against the hematologic cancers, such as leukemias and lymphomas, but can have side effects, such as the cytokine release syndrome (CRS), and neurotoxicity (*van den Berg et al., 2025*) Existing research tries to improve CAR T-cell survivability so that they can withstand exhaustion and evolve to adverse tumour settings. Strategies are optimising CAR designs with co-stimulatory domains such as 4-1BB, and CRISPR for functional efficiency with tumour signals. Modulation of toxicities is still an issue of priority, and adaptable CAR and initiating early intervention with the medications, such as tocilizumab (*Stewart et al., 2025*).

In the face of success with blood cancers, CAR T-cell therapy struggles with solid tumours because of immune suppression and bad tumour microenvironments. Pursuit of targeted delivery and armoured CAR T-cells is investigated in clinical trials to increase the effectiveness of treatment (*Abken, 2025*). According to *Umair et al.* (*2025*), CAR T therapies for CD19 in acute lymphoblastic leukaemia (ALL) and diffuse large B-cell lymphoma (DLBCL) have given durable remissions, but Observation and treatment tactics developments are streamlining toxicity control. Furthermore, the researchers are developing the next generation of CAR designs to overcome defects in solid tumors (*Wang et al., 2025*).

3.3 Cancer Vaccines

Cancer vaccines constitute an emerging approach in the treatment of cancer; they are meant to activate the immune response to identify and destroy tumour cells (*Sarangi et al., 2024*). Such vaccines apply the tumour-specific antigens that trigger cytotoxic T lymphocytes to attack cancer cells. There are different types of cancer vaccines developed: peptide-based, nucleic acid-based (DNA or mrna), viral vector-based and cell-based vaccines. One such example is Sipuleucel-T, which has enhanced survival in metastatic prostate cancer, where other forms of research are being carried out about other forms of cancer like melanoma, lung and pancreatic cancer. But there are challenges as well, such as tumour heterogeneity and immune evasion, which become the focus of the next strategies to improve delivery systems and personalise vaccine development (*Sarangi et al., 2024*).

HR-HPV and in particular types 16 and 18 are important in cervical cancer progression, with persistent infection and pre-cancerous lesion development. Prophylactic HPV vaccines have demonstrated potential in containing diseases related to HPV (*Kabir et al., 2025*). Therapeutic vaccines targeting the E6 and E7 oncoproteins are under research, showing promise for curing current infections and treating cervical intraepithelial neoplasia (CIN) and advanced cervical cancer when used in combination with other cures. Even though there are no approved therapeutic HPV vaccines yet, tests underway indicate that they may be essential for preventing cervical cancer (*Zheng et al., 2024*).

Although highly effective, prophylactic vaccines such as Cervarix and Gardasil have not lessened the impact of cervical cancers as a major global health challenge, with an approximately 10% increase in new cases from 2020 to 2022 (Research is also into designing next-generation vaccines that offer broader protection and greater efficacy especially second generation vaccines against the conserved L2 protein of HPV type. New vaccine delivery approaches, through the intranasal and oral routes, are being studied to increase efficacy and accessibility (*Amiri et al., 2025*). *Farrokhi et al. (2025)* highlight the importance of vaccines in preventing infectious diseases and specific cancers, emphasising the role of prophylactic vaccines against oncogenic viruses like HPV and Hepatitis B Virus in reducing cancer incidence.

3.4 Challenges

Cancer nano-immunotherapy provides exciting developments in oncology in terms of improvements in the effect and selectivity of immunotherapeutic approaches using nanotechnology. However, clinical application remains checked by such challenges as threats of autoimmunity and tumour immune evasion. Overactive immune responses can harm normal tissues, and evasion of detection by down-regulation of antigen presentation and secretion of immunosuppressive factors by the cancer cells may aid cancer cells to escape the body's defence mechanisms.

Nanotechnology may resolve these problems by facilitating selective delivery of immunomodulatory agents to the tumour microenvironment (TME), stimulating the local immune reactivity, and limiting the systemic toxicity. However, the sources of concern include biosafety of the nanomaterials, complexity of the manufacturing (*Wang et al., 2025*). Furthermore, the gastric adenocarcinoma (GAC) is still a global health challenge, and immunological checkpoint inhibitors (ICIS) with PD-1/PD-L1 and CTLA-4 targeting demonstrate promising efficacy in GAC treatment (C*hen et al., 2025).*

4. GENE AND CELL-BASED THERAPIES

Gene and cell-based therapies have appeared as principle approaches in cancer management, providing highly specific tumour cells while also regulating the immune response. Among them is CRISPR/Cas9 technology, which allows one to make site-specific gene edits without having to worry about the safety issue that surrounds viral vectors (*Uddin et al., 2020*). This pioneering strategy has been used to engineer immune cells, including CAR-T, CAR-NK cells, to overcome tumour-derived immune suppression (*Hossain et al., 2020*).

A second potentially useful strategy is suicide gene therapy, which involves delivering genes which encode enzymes such as HSV-tk or cytosine deaminase into tumour cells. This strategy activates selective cell death after the administration of a prodrug and can stimulate the immunogenic cell death, leading to the improvement of the general anti-tumour responsiveness (*Khoshandam et al., 2023*).

The therapy for CAR-T has shown great recovery rates, especially in the treatment of durable remissions in hematologic cancer. Its ability to perform, however, may be impaired by some of the challenges, including cytokine release syndrome, neurotoxicity, antigen escape and reduced efficiency in treating solid tumours (*Sterner & Sterner, 2021*). To overcome these limitations, engineered mesenchymal stem cells (MSCS) are being studied and they can home to tumour sites and can be modified to express anti-tumour agents like cytokines or prodrug-converting enzymes (*Shi et al., 2025*)

However, unaltered MSCs may unintendedly support tumour growth by immunosuppression and angiogenesis (*Antoon et al, 2024*). Although these state-of-the-art techniques offer great prospects for precision cancer treatment, difficulties associated with delivery efficiency and resistance of the tumour still become major hindrances that must be overcome for the best therapeutic results.

4.1 CRISPR/Cas9

CRISPR/Cas9 gene editing is accelerating cancer treatment, but the problems of off-target effects and delivery hinder it. CRISPR delivery is advanced with a reduction of the toxicity thanks to nanomedicine innovations, especially lipid nanoparticles. Other protectors of CRISPR components include such carriers as polymeric and gold nanoparticles. Functionalized chitosan nanoparticles are a promising non-viral delivery system owing to their biocompatibility and the stability of resulting complexes with nucleic acids, facilitating cellular uptake. Changes by targeting ligands improve cell targeting in cancer cells (*Nawaz et al., 2025*).In head and neck squamous cell carcinoma, we observed viability loss at 60% in vitro and a 90% inhibition of tumour growth in vivo when using a lipid nanoparticle delivering Cas9 mrna and sgRNA against SOX2 (*Masawry et al., 2025*). CRISPR/Cas9 also targets muscle-invasive bladder cancer to identify relevant genes associated with the development of the tumour and drug resistance. Despite risks of DNA alteration, combining CRISPR with nanoparticles could enhance treatment effectiveness (*Smith et al., 2024*).

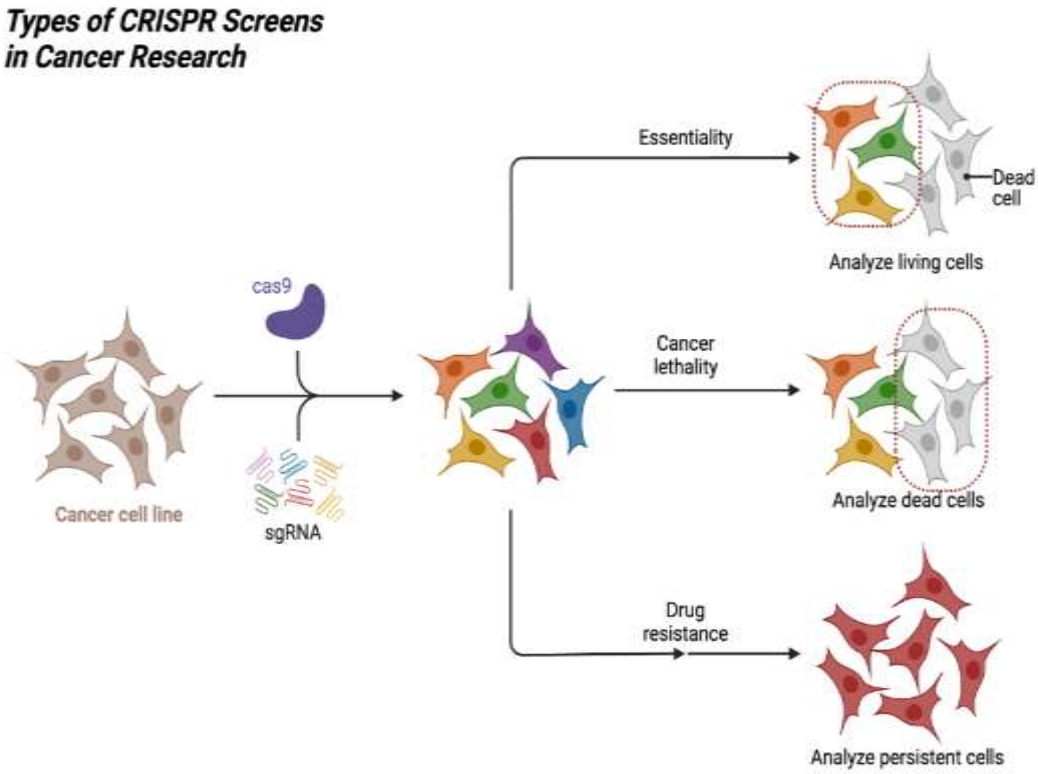

Fig 5: Types of CRISPR screens in cancer research.

4.2 RNA-Based Therapies

RNA-based treatments have advanced in modern medicine, providing a specific and effective cure. Gene silencing through RNA interference (RNAi) is, however, achieved via small interfering RNA (siRNA), thereby degrading disease-causing mRNA, beneficial in cancers and genetic disorders. The mRNA vaccines have, however, gained prominence after the COVID-19 pandemic. These vaccinations are promising for solid tumours and haematological malignancies, meaning that RNA-based treatments may be defining in personalised cancer treatment (*Miao, Zhang, & Huang, 2021*).

RNA stability, selective delivery concerns persist, yet the efficiency of LNP systems has expanded the therapeutic potential. A promising area for RNA therapeutics in cancers including melanoma and breast cancer has been revealed in clinical trials (*Ranga, 2025*). siRNA is a leading class for the suppression of harmful gene expression, whereas mRNA vaccines provide rapid development and strong immunogenicity. Innovative strategies that are applied to loaded RNA nanoparticles target liver tumours and overcome the problem of instability (*Yuan et al., 2024*). Nevertheless, RNA molecules can trigger innate immune sensors, triggering unwanted inflammation responses, which pose challenges for RNA therapeutic design (*Chauhan et al., 2025*).

4.3 Stem cell-based technologies

The stromal cells used in this study are Mesenchymal stem cells (MSCs) with multipotential differentiation capability towards several cell types, among which are osteoblasts, chondrocytes and adipocytes. Initially, separated from the bone marrow, they also exist in the kind of tissues such as the adipose tissue and the umbilical cord blood. MSCs possess an intrinsic ability to migrate to inflammatory sites and tumours, and hence potential vehicle systems for anti-tumour drugs of low immunogenicity (*Boopathy et al., 2025*). More specific studies on candidate species have focused on genetically manipulating MSCs to enhance their therapeutic function in the form of overexpression of certain agents, such as cytokines and oncolytic viruses (for on-target treatment) (*Shi et al., 2025*)

Another focus of interest is adipose-derived stem cells (ADSCs) and their ability to capitalise on their native homing to carry therapeutic agents to glioblastoma loci (*Bardhan et al., 2025*). More to this, MSCs can be modified to provide anti-tumour cytokines, for example, TRAI, stimulating apoptosis in cancer cells, saving the normal cells (*Singh et al., 2025*). The study that they conducted recently shows the complex association between MSCs and microbes and can facilitate or suppress the efficacy of MSC therapy (*Kord-Parijaee et al., 2025*). Exosomes, a drug-delivery vesicle obtained from MSC-derived exosomes (MSC-Exos), are novel in that they inhibit chemotherapy toxicity, while rerouting critical signalling pathways to trigger apoptosis of cancer cells (*Harrell et al., 2025*). Overall, MSCs present promising indications in terms of regenerative medicine and chemo-targeting and stress; therefore, the importance of further in vitro studies for the sake of secure clinical realisation.

4.4 Ethical and technical hurdles

Gene and cell-based therapies have made an entry into the treatment landscape of cancer, adopting personalised yet curative modalities. Nevertheless, despite their promise, such therapies are fraught with considerable ethical and technical challenges that should be very carefully addressed before widespread clinical use. One of the most critical issues is the safety of gene editing techniques, including CRISPR-Cas9, at which their unproductive off-target impacts may cause genetic abnormalities or new diseases (*Gbaraba et al., 2025; Chand et al., 2025*). In addition, the long-term effects of inserting genetically modified cells in patients are not well understood, invoking worries in oncogenesis, immune rejection and unpredictable toxicities (*Amin et al., 2025; Raj & Kumar, 2025*).

Technological issues, such as the ability to target precisely, efficient delivery, as well as the ability to control the gene expression, make the clinical translation of such therapies even more difficult. Ethical concerns, including fair access, informed consent and abuse of gene editing technologies, complicate it (*Gbaraba et al., 2025*). *Chand et al* (*2025*) provide an extensive overview of advances in the last decade of gene therapy in neurological disorders, along with critical ethical and technical barriers. The author points out that while gene therapy presents exciting ways to treat previously untreatable neurological diseases, the safety of gene editing is a significant concern, and through off-target effects, it could disrupt essential genes and furtherly compound the problem.

5. NANOTECHNOLOGY IN CANCER TREATMENT

Nanotechnology is an emerging area in contemporary technology, and it plays a useful role in the fight against cancer. Researchers focus on utilising nanoparticles to enhance light-based treatments, such as photodynamic therapy (PDT) and photothermal therapy (PTT). These methods improve specificity towards dysplastic cells, significantly reduce the destructive effects on normal cells, and avoid the deficiencies of orthodox systems. Gold nanoparticles and quantum dots are just among the many nanomaterials allowing precision delivery of therapeutics. The concept of theranostics is important, promoting multifunctional nanocarriers for simultaneous imaging and therapy. Existing improvements are the blending of light-activated agents with nanostructured materials to increase effectiveness and decrease toxicity.

In addition, drug resistance in this case for the treatment of cancer should necessitate the utilisation of nanotechnology. Small nanoparticles will deliver drugs when responding to tumour-specific triggers, also enhancing the drugs' accumulation at tumours via enhanced permeability and retention (EPR) effect. Another study highlights the interplay between the human microbiome and immune-oncology, suggesting that nanotechnology can modulate the microbiome to enhance cancer treatment outcomes. The nanoparticles in the form of liposomes are described as an efficient delivery method for immunotherapeutic agents. immunoresponse effects of which clear the ground for precision immuno-oncology (*Castillo-Rivera et al., 2025; Eskandar, 2025; Das et al., 2025*).

5.1 Nanocarriers

Nanocarriers have emerged as a promising discovery in cancer therapy as carriers of chemo-agents through such as liposomes, dendrimers, and polymeric nanoparticles. Current studies focus on difficulties in tumour targeting and the contributions of the tumour microenvironment (TME) and the enhanced permeability and retention (EPR) effect responsible for accumulating nanocarriers in tumour tissues because of the abnormal tumour vessel structures. Targeted nanoparticles procedures that concentrate on the change of nanoparticles' surfaces via tailing of ligands, such as folic acid and antibodies, have demonstrated further to raise cancer specificity and overcome multidrug resistance (*Saraf & Sharma, 2025*).Other investigations confirm the dependence of the EPR effect on pathologic abnormalities of vessels, which can be normalised using the physical methods (hyperthermia) and pharmacological agents. Such methods enhance the vascular permeability properties to enhance nanoparticle delivery. The design factors of nanocarriers, including size, shape, and surface properties, have a substantial effect on their efficacies (*Vagena et al., 2025*). Nanocarriers such as liposomes, polymeric nanoparticles are designed to improve the solubility and stability of drugs, targeted delivery and systemic toxicity associated with the conventional method of drug delivery. A realisation of such as an immune system's clearance is of paramount importance to their efficacy that such as PEGylation solutions (*Sengar et al., 2025*).

Al Yahyai and Al Kalbani (*2025*) discussed the development of nanocarrier-based systems for breast cancer, highlighting hybrid nanocarriers, which combine the strengths of liposomes and polymeric nanoparticles to promote drug bioavailability and delivery at tum Furthermore, possibilities of using nanocarriers are explored in early cancer detection and imaging (*Yahyai & Kalbani, 2025*). A new study classifies nanocarriers into five major groups. Liposome, polymeric nanoparticle, micellar, dendrimer and SLn. The individual characteristics of the kinds enhance their therapeutic properties – biocompatibility, stability and controlled release (*Rao et al, 2025*).

5.2 Theranostics

Theranostics (therapeutic and diagnostic together) is a promising way to treat cancer by bringing together diagnostic imaging with targeted therapies. This multidisciplinary approach increases cancer management precision, to make tracking more accurate and responsive to personal intervention, especially in advanced nanomolecular materials (*Patel et al., 2025*).

Carbon Quantum Dots (CQDS), a major application of nanotechnology, have been keenly looked at in cancer treatment, considering that they are unique in photoluminescent properties as well as being biocompatible and surface functionalized.CQDs are designed for the specific surface functionalization for drug delivery and conjugated with tumour-specific ligands and can be used in PTT and PDT, generating ROS under controlled irradiation (*Bhamare et al., 2025*). Their programmable properties (which are achieved using a bottom-up hydrothermal route) allow for accurate control of fluorescence intensity, as well as drug release kinetics, both in vitro and in vivo. The fluorescence images have demonstrated the high tumour accumulation because of the enhanced permeability and retention (EPR) effect, with cytotoxicity assays reporting significant activity against cancer and low effects outside the target (*Patel et al., 2025*).

Quantum dots have an important role towards theranostics and in allowing tracking of tumours as well as delivering therapy in an integrated system. Biocompatible ligands minimise toxicity, and their applicability forms formulticolour and near-infrared (NIR) imaging allows real-time, high-resolution monitoring of tumour development (*Matini et al., 2025*). New developments in this area include nonmagnetic inorganic/organic core-shell nanoconstructs with simultaneous capacity for drug delivery and diagnostic imaging exhibiting enhanced biocompatibility, stability, as well as tunable drug release profiles because of optimised surface chemistry and distribution in size (*Vas Hu et al., 2025*) summarise the developments in nanotechnology-based diagnosis and therapy of bladder carcinoma using nanotechnology, exemplifying the value of nanomaterials in improving imaging tools such as MRI, and fluorescence imaging They also concern innovative nanostructures that overcome problems like poor drug solubility and drug resistance to traditional approaches.

5.3 Benefits

The use of nanotechnologies is revolutionising the discipline of oncology by increasing the bioavailability of a drug and lowering systemic toxicity. Former fabricated nanotransporters, such as CNDS (carbon nanodots), have been promising, since they adsorb preferentially to tumour tissues, causing more favourable treatment effects and less toxicity than the existing devices. High photoluminescent properties were found for CNDS, which, with anticancer agents like doxorubicin and curcumin, displayed better uptake by cells and cytotoxicity over free drug formulations, low hemolytic activity and high biocompatibility.

In the therapy of melanoma, the use of nanoparticles such as liposomes and dendrimers promotes the solubility of drugs and targeted delivery. Advances consist melanoma melanoma-targeted polymeric formulations to increase the bioavailability of antimelanoma compounds but minimise systemic toxicity level and co-delivery of imaging agents and therapies (*Kanugo et al., 2025*). Inventions proceed with smart polymer-based nanocarriers, which are owed to react to specific tumour-microenvironment stimuli (e.g. pH, temperature), to achieve site-specific drug delivery. For example, pH-sensitive nanoparticles release their chemotherapeutic load at acidic tumour conditions. In addition, the use of biodegradable implants loaded with nano-prepared drugs allows for continuous localised delivery to tumours (*Patel, 2025*).

Kumar and Mangla (2025) speak of the use of nanobots in the control of gynaecological cancers, their high degree of tumour targeting and drug delivery in cases of ovarian cancers. Innovative uses include manipulation of magnetic field presiding over nanobots for treatment in cervical and endometrial cancers, and smart nanocarriers functionalized with folate or transferrin for targeted therapy against cervical and endometrial cancers. Moreover, a work for nanotechnology-based treatments addresses patient-specific factors, including age and gender, that will influence drug bioavailability and results of treatment. As was revealed by the findings, the metabolic difference and the change in a hormone affect a changed uptake and clearance of the nanoparticles; this emphasises the need for the proposed individual-determined strategy in tackling cancer (*Ike et al., 2025*)

5.4 Concerns

Advancements in nanotechnology have recently given rise to multifunctional systems that solve the major problems associated with cancer therapy: biocompatibility and systemic clearance. *Yu et al* (*2025*) created composite capsules for controlled release as well as for targeted delivery that improved circulation and tumour accumulation. Acetalated dextran (Ac-DEX), still a biodegradable polymer, can allow site-specific delivery in acidic tumour environments, thus enhancing the effectiveness of chemotherapy and immunotherapy (*Thakkar & Bhattacharya, 2025*). According to *Xu et al.* (*2025*), mesoporous silica nanostructures (MSNS) deliver the CRISPR/dCas9-SAM system effectively to activate a tumour suppressor gene in bladder cancer. Hybrid systems in which nanoparticles and gels are doped together were introduced by *Kim* (2025) for localised, sustained release of drugs with low toxicity. These innovations show the capability of properly designed nanocarriers to turn the cancer nanomedicine to a clinically available level.

6. ARTIFICIAL INTELLIGENCE AND BIG DATA IN ONCOLOGY

This overview is interesting for the revolutionary position of big data and artificial intelligence in cancer research, especially precision oncology. AI helps to combine heterogeneous datasets, including genomics and/or clinical records and allows the development of personalised treatments and detection of new biomarkers. A significant contribution is a machine-learning system for large cancer data analysis that overcomes issues of data curation in terms of quality and ethics, calling for interdisciplinary working (*Wu et al., 2024*).

In addition, the review addresses the incorporation of AI, ML and big data in radiation oncology with the focus on utilisation of computer vision (CV) in digital pathology, and Natural language processing (NLP) in clinical documentation (*Zhu et al., 2025*). AI-driven models for pancreatic cancer reveal the necessity of early identification and precision of diagnosis, as well as clinical implementation obstacles regarding the variability of data, and ethical aspects (*Zhao et al., 2024*). Finally, the progress in the use of AI for diagnosing and treating pancreatic cancer addresses the search for early-stage pointers (s) via imaging modalities such as CT and MR, minimising clinical workflow difficulties to enhance patient outcomes in palliative care (*Zhang et al., 2025*)

6.1 Role in diagnostics: Radiomics, AI-assisted imaging for early detection

Current research emphasises that AI-mediated radiomics is revolutionising the field of cancer imaging by being able to extract quantitative features that are out of the human perceptual range. According to *Cè et al.* (2022), AI models are being created for a variety of oncological duties, such as patients' risk stratification and lesions' automatic detection. Noting substantial progress in the diagnosis and characterisation of lung cancer nodules early with machine learning and deep learning methods over imaging modalities such as low-dose CT and PET-CT, *Gandhi et al.* (2023).

Bajwa et al. (2021) state that automated image classification has become a primary area of use for AI in healthcare, and many such tools have received FDA and CE approval. AI's ability to provide analysis on images, in most cases, matches that of human experts. *Ahn et al* (2023) reported that the addition of PET/CT radiomic features to TNM staging augments risk stratification for early-stage cancers.

Najjar (2023) sees the radiomics potential in predicting disease development for personalising the therapy. The experts, however, warn that the field still needs development with large-scale data sharing, standardised protocol, and rigorous validation of research for use in practice. Ethical and regulatory issues also need to be discussed (*Najjar, 2023; Mennella et al., 2024*). In general, the evidence appears to hold a bright future for AI radiomics in cancer detection and diagnostic workups.

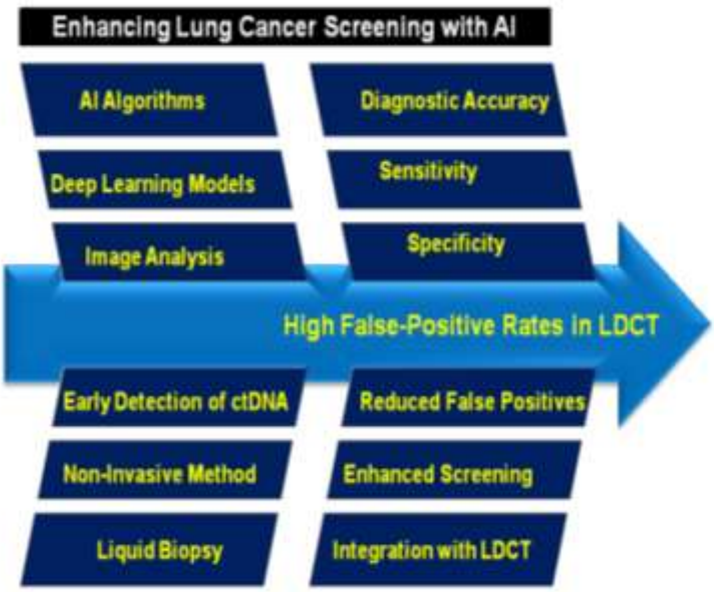

Fig 6: Enhancing lung cancer screening with AI

6.2 Predictive modelling: Treatment response prediction using machine learning on multi-omics data

The synergy of the machine learning (ML) approaches with the omics data is promoting oncology studies by utilising mechanisms such as support vector machines and deep learning to understand complex data collection from genomics, transcriptomics, proteomics, and metabolomics. This integration helps in biomarker discovery, cancer pathogenesis process understanding, overcoming issues of heterogeneity of data and demands for standardised preprocessing methods for making reliable ML models in clinical environments (*Cai et al, 2022*).

The talk addresses issues of data privacy, integration issues and model understanding, future implications being suggested to concentrate on model pre-training, and knowledge integration to improve biomedical applications (*Liu et al., 2025*). Also, a novel integrative multi-omics framework has been developed to discover genes that are associated with long COVID-19 using approaches such as Transcriptome-Wide Mendelian Randomisation (TWMR) and Control Theory (CT).

The present research assigned Long COVID patients into three populations, depending on the symptoms based on the data (*Pinero et al., 2025*) and developed an open-source application for data exploration. In addition, the focus of the Systems Biology of Personalised Medicine highlights the need to use multi-omics and ML in combination to enhance predictive modelling in oncology, defining major biomarkers and molecular pathways for personalised therapeutic tools in the context of a remarkable improvement on the precision oncology (*Fawa et al, 2023*)

6.3 Precision medicine: AI for patient stratification, clinical decision support

The combined use of AI, ML, and big data analytics in radiation oncology better enables precision medicine by optimising patient stratification as well as clinical decision support. The authors illustrate the use of computer vision (CV) in digital pathology and radiomics, demonstrating how AI models can derive imaging features to forecast any treatment outcomes and individualise treatment. In addition, they explain the use of natural language processing (NLP) to analyse clinical documentation to improve knowledge assessment and quality assurance. Despite barriers such as data heterogeneity and a lack of standardised protocols, there is a lot of possibility for AI/ML in enhancing care in radiation oncology (*Zhu et al., 2025*).

The talk further extends to AI in tailored medicine for head and neck cancer, in which advanced ML algorithms forecast patient-specific therapy response and optimise treatment planning precision. However, difficulties in the standardisation of data and the interpretability of AI predictions have to be overcome for efficient clinical implementation (*Karthikeyan et al., 2025*).

Moreover, AI issues in cardio-oncology are considered, and its ability to forecast and treat cardiovascular toxicity caused by cancer treatment is discussed. AI models which rely on ML and DL can process massive clinical, imaging and genomic data to predict cardiac events, taking a patient profile. According to the authors, it is important to incorporate AI tools into the process of clinical workflow for improved early detection and prevention measures concerning cardiovascular complications for patients with cancer (*Guha et al., 2025*).

6.4 Limitations: Data privacy, need for high-quality datasets, interpretability of models

The introduction of Embodied Artificial Intelligence (EAI) into healthcare presents transformative possibilities in oncology as AI systems can now gain from their physical environments. The EAI techniques are grouped as perception, decision-making and actuation, useful for surgical robots, rehabilitation, diagnostics and personalised treatment planning. Validation of safe interaction with humans and AIs, as well as the shortage of learning data and the need for generalisation across clinical settings, are the key challenges.

From the study, we see possible directions for the design of robust datasets, interpretation of AI implementation, and adherence to subjective ethical standards of AI implementation (*Liu et al., 2025*). Further, Enhanced Multi-Layer Perceptron (EMLP) optimised through the worst moth disrupted moth fly optimisation (WMFO) has potential use in oncology-type jobs, including cancer risk prediction and imaging analytics. In the able work dedicated to the research of $C0_2$ forecasting, the EMLP-WMFO model exceeded the performance of standard methods, demonstrating better results in terms of Mean Squared Error and other metrics, revealing improved performance in the challenging oncological datasets (*Adegboye et al., 2025).* The work also discusses difficulties associated with training deep neural networks on synthetic data using Generative Data Augmentation to enhance classifier performance.

7. CHALLENGES AND LIMITATIONS

The area of cancer treatment has innumerable difficulties and restrictions. *Correia de Verdier et al.* (2024) address the development of MRI processing for brain tumour analysis, especially gliomas, where numerous characteristics of the tumour make consistent segmentation difficult. Though the BraTs dataset is accompanied by some materials, its small size and lack of variety are barriers. Yet *Zugazagoitia et al.* (2016) pursue broader matters in clinical oncology, documenting how tumour heterogeneity, resistance mechanisms, and systemic toxicity undermine the effectiveness of the treatment even when the therapies such as surgery, chemotherapy and immun They promote an integrated model of technological innovation with individualised strategies, involving advanced imaging, biomarker discovery, as well as genomic profiling.

Therapy resistance, including immunotherapeutics, is an enormous obstacle that many patients report variable responses. In addition, high price and lack of availability of innovative treatment present additional challenges. *Bisht et al.* (2025)

concentrate on doxorubicin, a popular chemotherapy for breast cancer, and explain its limitations, including the heart toxicity and drug resistance. They involve the investigation of recent approaches to delivering doxorubicin with the help of Nano carriers that may enhance the targeting of malignant cells without damaging normal tissues. Nevertheless, such sophisticated procedures are still challenged by a variation in response to patients and formulation problems.

7.1. DRUG RESISTANCE MECHANISM

The chemotherapy resistance in cancer is triggered by a range of biological mechanisms: the function of efflux pumps, the diversity of tumour cells, and genetic mutations. Such factors can result in treatment resistance because different cells in a tumour will react differently to treatment. Efflux pumps, including the P-glycoprotein, MRP1, and BCRP, are of major importance because they force the drugs out of cancer cells, making them less effective. The cancer stem cells also play a role in repairing damage better than traditional cancer cells do.

Scientists are developing ways, such as efflux pump inhibitors and gene-editing techniques such as CRISPR, to improve chemotherapy's impact (*Gu et al., 2024*). In addition, *Lei et al.* (2023) show that resistance is due to genetic changes, changes in signalling pathways, and support from the tumour microenvironment (TME). Tumours can stimulate survival pathways such as MAPK and PI3K/AKT, which the tumour microenvironment which protect from being attacked by the immune system, can protect.

As counter-measures, the use of polymer-based nanoparticles and liposomes for drug delivery is proposed. Combination of the uses of chemotherapy with immunotherapies or targeted therapies may affect several resistance pathways, and might result in better treatment successes (*Lei et al., 2023*). Overall, the interplay relationship between genetic alterations, signalling pathways and TME support is significant to understand, with a single target strategy possibly not viable (*Gu et al., 2025; Lei et al., 2023*).

7.2. TOXICITY AND SIDE EFFECTS

State-of-the-art cancer therapies, especially gene therapy and immune methods, lead to major concerns about toxicity. *Youssef et al.* (2025) discusses the risks and benefits of these precision methods while, observing that immune-related adverse events (irAEs) may result from overexcitement by immunity and thus affect healthy body parts like skin, liver, lungs, and brain For gene therapy, there is a risk of off-target effect, and CRISPR-cas9 or other technologies, while modifying the target, may inadvertently change non-target DNA which could cause long term damage.

The authors of the research emphasise the need for more effective control systems and monitoring to prevent possible malfunction and ensure patient safety, and point to a new medical application of nanocarriers: polymeric nanoparticles and liposomes, for safer gene delivery, but this can be potentially dangerous. The study also proposes that adding immune checkpoint inhibitors to gene therapies might increase treatment efficacy.

Oboma and Ekpenyong extend their work further to look at the difficulties in using these methods in prostate cancer. They report severe adverse effects, such as immune-related toxicity, as well as severe adverse events, such as cytokine storm caused by therapies such as viral gene delivery and CAR-T cells. The intricacy of human genes and tumour surroundings throws into question effects apart from the targets, in which healthy cells might non-intentionally be changed. Amongst these safety issues is to address the reach of the full potential of gene and cell therapies.

7.3 COST AND ACCESSIBILITY

A cost minimisation analysis. Low et al looked at the financial and logistics issues of cancer treatment, especially for HER2-positive breast cancer, when subcutaneous (SC) and intravenous biologic formulations are compared. Although S.C. therapies are paid at higher prices, they are time-saving, which reduces considerably indirect costs such as staff workload and patient clinic time costs. The study introduced the term “time toxicity”, focusing on the negative effects of longer therapies on patient productivity and quality of life. It also pointed out differences in the availability of therapy between public and private healthcare systems, highlighting persistent access challenges based on cost.

Feng et al investigated 2015 through to 2022 Medicare Part D data and identified that biosimilars have not brought patient cost reduction as pricing policies and refund schemes have compromised their savings potential. But, even though the biosimilars were on hand, the cost of payments for such drugs as filgrastim remained almost unchanged. This represents a remarkable disparity between market reverence and real affordability and calls for more patient safeguards. The ESMO Global Consortium Study (2023) built on the financial issues in cancer care and reported that while the patient in high-income countries enjoys better access with low out-of-pocket costs to cancer therapies, the ones residing in the low- and middle-inc In these regions 40% of essential chemotherapy drugs are only accessible at full patient cost, thus denying access to high benefit biological therapies.

Langfelder et al. (2025) performed a retrospective analysis in Milan, finding that even though biosimilars are less costly than originators, their adoption is dependent on prescribing and patient care practices. Cost savings can be realised at a price of maintaining treatment efficacy if originator biologics are switched to biosimilars. Monitoring and education at all times are important for the regular use of this medicine.

Ntais et al (2025) confirmed that while integrating biosimilars into the treatment of rheumatoid arthritis, this intervention decreased the cost considerably to enhance long-term sustainability in the healthcare systems. Their research showed that a switch to biosimilars might save huge amounts without affecting the quality of received care, promising similar results in resource-constrained oncology settings.

Potential of cellular and immunotherapies such as CAR-T notwithstanding, conversion of such into a clinical practice is hampered by high costs, equipment requirements, and disparities in availability. Geethakumari et al. observed that even though some academic institutions may be able to provide such therapies, specialised staffing and lengthy hospital stays help to drive up treatment costs, respectively. They suggested models for decentralised production and outpatient services to ease system-wide pressures, but financial sustainability continues to be a significant challenge, particularly in healthcare systems with limited funding.

7.4. ETHICAL CONCERNS

With the increasing spread of AI in biotechnology, *Joseph* (2025) discusses the importance of ethical tracking to walk hand in hand with innovation, most especially in agencies such as the NIH. Although AI-based diagnostics and therapies based on nanocarriers can improve the efficiency and availability of treatment, they cause grave challenges like algorithm bias, patient data privacy and equitable access. Joseph offers a plural-layered regulatory model with cross-disciplinary boards for ensuring ethical compliance as well as informed consent in particularly pointing out the lack of representation of certain communities in AI Training databases, which can taint treatment outcomes.

The ethical issues increase as the cancer gene therapy is explored, as discussed by *Chasta and Sheikh* (2025). They talk of next-generation gene-editing technologies such as CRISPR-Cas and mention the concerns regarding genetic privacy and patient autonomy, especially considering the world's current health inequality when it comes to the technologies available. They recommend holistic models of ethical conduct to deal with the problem.

Sahni and Shukla (2025) continue to look at the dual-edged nature of AI in cancer treatments and how it enhances diagnosis and treatment through superior drug delivery systems, and that ethical guidelines are necessary. Playing cards include genetic privacy, informed consent, and access disparities for marginalised settings. In general, the incorporation of ethical interests in AI-driven medicine is critical to make healthcare advances equitable and just.

8. FUTURE DIRECTIONS AND EMERGING TRENDS

The development of technology, specifically the adoption of artificial intelligence (AI) and machine learning (ML), has a great tendency to shape the future of cancer treatment. These technologies improve predictions, diagnostics, and therapy choices, and, in turn, clinical results, as AI-enabled medical devices are certified by regulatory bodies, such as the FDA (*Hamamoto et al., 2025*). There remain, however, struggles such as model over-fitting and a lack of visibility on AI decision-making processes.

Recent research has shed light on the benefits of having psychotherapeutic interventions such as Individual Meaning-Centred Psychotherapy (IMCP) and Mindfulness-Based Cognitive Therapy (MBCT) that have worked for cancer patients with advanced cases – to increase emotional resilience and quality of life (*Anghel et al., 2025*). Innovations in point-of-care (POC) diagnostics, particularly through CRISPR-based technologies, provide rapid and accurate testing solutions for various diseases (*Hassan et al., 2025*).

Biometallic ions, such as zinc, copper, magnesium and manganese, are coming to be an important part of cancer immunotherapy as they have the potential to modulate immune response and enhance therapeutic outcome (*Zhao et al., 2025*). Although limited, minimally invasive surgery (MIS) practices, including robot-assisted surgery, are getting mainstreamed. This development is further improved by the improvement in imaging technologies and integration of augmented reality (*Bobade & Asutkar, 2025*).

The integration of AI in use with robotic surgery provides real-time data analysis and decision support, ultimately to benefit surgical planning and execution. Additionally, advancements in genomics are facilitating personalised medicine, enabling more tailored surgical interventions (*Bobade & Asutkar, 2025*). Future research should concentrate on enhancing the accessibility and affordability of these technologies while streamlining the integration of genetic information into standard practices.

8.1 Tumour Microenvironment (TME)

The microenvironment of the tumour (TME) plays a fundamental role in cancer progression, treatment resistance, and metastasis, and it consists of diverse cellular entities, including stromal cells, immune cells and endothelial cells, as well as of extracellular matrix (ECM These elements promote tumour formation and h erewith add up to the resistance to the therapies. Fibroblasts, vasculature and other stromal and immune structures are an emerging target for cancer treatments with generally better outcomes (*Liu et al., 2025*).

Recent findings show how tumour-associated stromal cells interact with cancer cells, driving survival and therapy resistance.

Interestingly, high immune cell infiltration is linked to better survival outcomes, but excessive ECM remodelling is linked to more adverse outcomes (*Desai et al., 2025*). The TME not only promotes tumour expansion and immune evasion, but also plays a major role in hypoxic situations that activate survival way in cancer cells (*Bayat & Nahand, 2025*).

Molecular imaging has been transformed into the main tool for oncology to visualise the tumour immune microenvironment (TIME). PET and MRI among other imaging modalities are used to track immune responses and efficacy of therapy and allow for customised methods of care (*Wang et al., 2025*). The use of artificial intelligence in image analysis may support diagnostics and prognostics, illustrating that the prospect for attacking parts of TME to overcome therapeutic resistance exists (*Liu et al., 2025*).

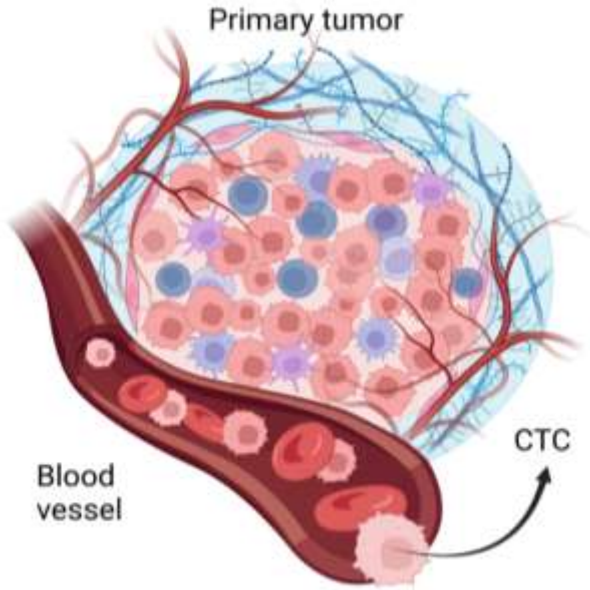

Fig 7: Tumour microenvironment of cancer

8.2. Microbiome-Cancer Axis

The gut microbiome largely modulates the immune response during cancer therapies, especially immunotherapy, thereby identifying the microbiome-cancer axis as an important focus for amelioration of therapy efficacy and lessening toxicity by microbiota-centred interventions. Different and balanced gut microbiome improves the efficacy of the immune checkpoint inhibitors (ICIs), whereas dysbiosis or imbalanced microbes diminish the therapy response and maximise adverse effects. People with better ICI responses are associated with specific microbial taxa such as Bacteroides and Ruminococcaceae family members, and microbial metabolism, such as short-chain fatty acids (SCFAs), modulates immune responses (*Mahmoudian et al., 2025*)

Dysbiosis treatment strategies include faecal microbiota transplantation (FMT), antibiotic therapies and dietary intervention, all targeting to promote positive immunotherapy (*Kim et al., 2025*). In addition, the gut microbiome affects pancreatic cancer progression and affects the effectiveness of systemic treatments through its role in keeping the intestine at homeostasis and the inflammatory state (*Zalila-Kolsi et al., 2025*). The components of a diet also influence gut microbiota composition and response to treatment. High fibre and ppolyphenol-richdiets diets will support healthy microbes, whereas high fat and low fibre diets are associated with dysbiosis and immunotherapy ineffectiveness (*Abdeen et al., 2025*).

8.3 Combinatorial approaches

Combinatorial approaches overcome ICTS' limitations, and strategies to either eliminate resistance or improve clinical outcomes are presented. Despite the revolutionisation of cancer treatment through ICTS, most patients fail to respond in durable ways because of multiple resistance pathways. The authors promote the creation of combination therapies based on a profound knowledge of the intricate human antitumor immune response biology (*Goswami et al., 2024*). They highlight the necessity to translate clinical observations into immunocompetent preclinical models to test particular biological mechanisms.

The computational techniques and machine learning are of paramount importance in the combination of clinical and preclinical studies reports resulting in the discovery of relevant pathways for personalised combination approaches. Sifting through 54 studies presents the application of AI in biomarker discovery, prediction of the patient's response, and optimising combination therapies, with an accuracy rate of 85-95%, a far higher number than compared to conventional methods (*Olawade et al, 2025*) AIs analysis utilizes genomic, transcriptomic, and proteomic data for the prediction of patient responses to immune checkpoint inhibitors (ICIs), therefore, as a vehicle to better care.AI also assists in the exploration of novel therapeutic targets such as neoantigens and immune checkpoints (*Mao et al., 2025*), through such methods of machine learning as unsupervised methods. Further, AI optimises drug dosing and scheduling to maximise the therapeutic effect and minimise adverse effects, strengthening the viability of individualised cancer therapies.

The review highlights the possible combination of ICIs with other treatments, including Radiation and targeted therapies, to capitalise on their immunogenic effects. However, barriers including high toxicity and strict patient selection requirements exist, and clinical trials are therefore required to optimise these combination strategies towards improved patient outcomes (*Zhang, Zhao et al, 2024*). Lung cancer immune evasion factors,tumour-intrinsic and extrinsic, are also addressed, investigating interventions such as microbiome modification to enhance outcomes of immunotherapy (*Garg et al., 2024*). Personalising treatment based on each patient's unique genetic and epigenetic profile is essential for overcoming resistance and enhancing the efficacy of lung cancer immunotherapy.

8.4. Next-gen tools

The breast cancer research is being transformed by Biotechnologies, especially organoid models and single-cell sequencing technologies. Organoids, which are developed from patient-specific stem cell lines, give access to three-dimensional culture systems enabling high-throughput drug screening that examines therapy responses and resistance processes in an individualised context. Single-cell sequencing allows for unmatched deconstruction of tumour heterogeneity, improving diagnosis accuracy and therapeutic approach (*Dhoundiyal et al., 2024*). This study makes distinctions between drug-sensitive and drug-resistant cells and will open a platform for expeditious therapeutic profiling and personalised treatments (*Leslie et al., 2018*). Combination of organoid systems with single-cell transcriptomics reveals information about disease progression and therapeutic reactions. Single cell profiling suggests that the IELs envelop the epithelium and respond promptly to cancer-seeking biologics to inflame against normal tissue and relate to clinical results. Together, these technologies improve our knowledge regarding cellular heterogeneity and intercellular communication and hold key insights into the mechanisms and interventions of breast cancer (*Gjeta et al., 2023*).

9. DISCUSSION

The cancer treatment has gained some amazing ramifications lately, transforming the face of life-threatening disease treatment. With cancer being a major threat, researchers keep looking for innovative ways to invent treatments that can safely attack and kill tumours. Cancer incidence rate has been increasing over the past five years to about 12.8%, which calls for an immediate need for superior therapeutic choices.

Current therapies today are now offering hope to patients who had little choice in the past, with new tactics offering better survival and lower side effects than standardised forms of treatment such as chemotherapy, surgery and radiation. Among these are targeted treatments such as Tyrosine Kinase Inhibitors (TKIs), which prevent the most affected molecular pathways leading to cancer. For instance, the imatinib displayed high efficacy in chronic myeloid leukaemia (CML), and osimertinib has progressed in non-small cell lung cancer (NSCLC) by targeting mutations specific for cancer cells only. Furthermore, monoclonal antibodies, including trastuzumab, have significantly revolutionised the treatment of breast cancer because they target the specific HER2 receptor.

Another promising front in cancer therapy is the development of immunotherapies – tools to stimulate the body's immune response to fight cancer. Immune checkpoint inhibitors such as nivolumab and pembrolizumab have exhibited high success in melanoma and NSCLC treatment. However, to exploit their full potential, a multidisciplinary approach is critical in the risk management of immunotherapy. CAR T-cell therapy is one of the promising areas of health, as it exists in the form of genetic modification of patients' T-cells, which turn against cancer cells; promising results have been achieved, especially in haematological cancers, though efficient use in solid tumours is still being researched

Gene and cell therapies are another sphere of transformation in cancer treatment. Techniques like CRISPR/Cas9 gene modification promise to fix genetic mutations that cause cancer development, making it possible for exact modifications of oncogenes or tumour suppressor genes, and perhaps new cures for genetically based cancers. Nevertheless, there are hindrances to safely and efficiently delivering these gene-editing tools to tumour cells. In the same manner, RNA-based therapies Rsilencing RNAi, Sirna, RNA), as well as the mrna vaccines, can offer exciting strategies for targeting cancer-specific genes while enhancing the immune system capabilities to fight cancer.

Cancer treatment is revolutionised by nanotechnology as well. Innovations under development include liposomes, dendrimers and polymeric nanoparticles as nanocarriers for targeted delivery that drastically reduces off-target effects and minimises systemic toxicity. These nanoparticles present hybrid functionality in the field of theranostics, combining imaging and therapeutic functions emanating from a homogenous system.

Integration of artificial intelligence (AI) into oncology has tremendous potential, and in the field, precision and personalisation may potentially improve the success rates of treatment. AI is used to construct predictive models to assess patient reactions to different therapies, so that clinicians can customise treatment according to individual profiles. Specifically, AI-supported imaging and radiomics support early cancer detection, which is essential for enhancing patient outcomes to be enhanced. However, issues like data privacy, a need for high-quality datasets, and the interpretability of AI models in the clinical space need to be solved.

Despite these improvements, however, problems remain, such as drug resistance resulting from genetic mutations, tumour heterogeneity and the skill of the tumours to change during therapy. A normalised method of clinical studies is needed to address the challenge. The prohibitive costs of biologic treatment and lack of access to sophisticated therapies point to a critical necessity for fair approaches in healthcare. With cancer treatments becoming more complex, the economic burden on patients and healthcare systems can only increase, making accessibility relevant, especially in low-income communities.

There is the future of cancer therapy in attempts to identify tumour microenvironment (TME) alterations, attempts to study links between the microbiome and cancer, as well as attempts to develop combinational strategies, especially the combination of immunotherapies with other therapies such as radiotherapy. State-of-the-art approaches, such as the use of organoids for drug screening and single-cell sequencing approaches to unveil heterogeneity in tumours, will give important information regarding the dynamics of cancer and treatment resistance.

Conclusively, the current revolution of cancer care announces a new age of oncology influenced by the intersection of targeted treatments, immunotherapy, gene editing, nanotechnology and artificial intelligence. The opportunity to revolutionise cancer treatment as more personalised, efficient and affordable is huge. However, Kazdan AS (2020 noted that the problem of treatment resistance, toxicity, cost, and unequal access is an important issue because these advanced therapies are needed by all patients. The ultimate vision is to redefine cancer as a manageable condition rather than a life-threatening disease, offering renewed hope for patients worldwide.

10. CONCLUSION

While the treatment landscape for cancer is undergoing a complete overhaul due to advances in targeted therapies, Immunotherapy, gene and cell-based, and nanotechnology fields, the one which is ripe for disruption is Surgical Oncology. Such innovations not only improve the accuracy and effectiveness of the treatments, but also develop a hope for treating cancer as a chronic condition rather than a deadly disease. Yet such obstacles are still enormous, such as treatment resistance, toxicity, cost-prohibitiveness, and inequity in access to state-of-the-art treatment. These problems require a collective global initiative involving sustained research, just health policies, and innovation, patient-inclusive. Future avenues seeking to understand tumour microenvironment, the microbiome and cancer role and combinatorial therapy, are fascinating prospects to address current limitations. The goal of truly personalised, safer and universally accessible cancer care is becoming more and more possible due to continued vigour in scientific and technological developments

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