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Recent Developments in Anticancer Drug Discovery and Design

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Abstract:

Cancer continues to be one of the significant diseases in terms of global public health concern and thus the development and design of novel strategies for anticancer drug discovery become a perpetual need. The advances made in various fields such as molecular biology, medicinal chemistry, immunology, nanotechnology, and computer science have made it possible to move beyond the traditional chemotherapy to precision-oriented and mechanism-based treatment of cancers. The aim of this review is to discuss the recent advancements in molecular targeting, precision medicine, biomarker guided drug design, synthetic lethality, drug resistant therapy, and tumor microenvironment targeting. Moreover, the article touches upon the increased use of AI, computer-aided drug design, multi-omics approaches, CRISPR-based screens, patient-derived models, and novel trial designs for accelerating cancer drug development. Although much success has been achieved in this field, obstacles like tumor heterogeneity, drug resistance, biomarker validation, manufacturing difficulties, and translating the findings into practice still exist. In general, the combination of precision medicine, computational approaches, and multidisciplinary collaboration is anticipated to facilitate the development of safer and more efficient anticancer drugs.

Keywords: Anticancer Drug Discovery; Drug Design; Precision Oncology; Molecularly Targeted Therapy; Immunotherapy; Antibody–Drug Conjugates; Artificial Intelligence; Nanomedicine; Multi-Omics; Precision Medicine.

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1. INTRODUCTION

Cancer still stands out among the most significant causes of death globally and continues to be a significant public health problem even in light of the remarkable developments in the diagnosis and treatment of cancer[1]. The conventional methods of therapy, such as surgery, radiotherapy, chemotherapy, and hormone therapy, have been instrumental in saving lives through their ability

to increase the rate of survival; however, the effectiveness of these methods has been impeded by factors such as lack of selectivity of the tumor, systemic toxicity, drug resistance, recurrence of tumors, and variability of response to treatment among individuals[2]. These factors have fuelled efforts towards developing new anticancer drugs to target the molecular pathways of tumor development, progression, and metastasis[3].

In the recent past, new developments in the field of cancer research have brought about new ways in which drugs for treating cancer can be designed thanks to the introduction of precision oncology, immunotherapy, protein targeting, nanotechnology, and artificial intelligence-assisted drug design[4]. Developments in sequencing genomics, multi-omics, computing modeling, high-throughput screening, and biomarker discovery have provided scientists with the ability to identify new drug targets that result in the designing of safer, selective, and efficacious anti-cancer drugs. In addition, novel approaches such as antibody drug conjugates, bispecific antibodies, protein degrading compounds (PROTACs), cancer vaccines, cell and gene therapy, and smart delivery of drugs are enhancing cancer treatment for both solid tumors and hematological cancers[5].

1.1 Background and Context

The progress made in anticancer drug discovery during the past few decades has been tremendous, shifting from conventional non-specific cytotoxic chemotherapy to treatment modality involving specific targeting of molecular aberrations in cancer cells. Discovery of genetic aberrations, aberrant signaling pathways, tumor micro-environment and immune evasion mechanisms resulted in the finding of various therapeutic targets[6]. On the other hand, advances in structure-based drug design, computational chemistry, artificial intelligence, nanotechnology and translational medicine have expedited lead optimization and improved the efficiency of drug discovery process. All these advancements have remarkably increased the options for drug development while highlighting the significance of biomarker guided and personalized medicine[7].

1.2 Objectives of the Review

The primary objectives of this review are:

- To review recent developments in molecular targeting therapies, precision oncology, and structure-based anticancer drug design.
- To explore new approaches to therapy, such as immunotherapy, antibody-drug conjugates, protein degradation strategies, nanotechnology, and cell and gene therapies.
- To consider the role of artificial intelligence, multi-omics, advanced screening methods, and patient-derived models in contemporary anticancer drug discovery.
- To explore the present-day challenges, translational hurdles, and future directions for anticancer drug development.

1.3 Importance of the Topic

The rising global burden of cancer coupled with the increasingly complex nature of tumour biology and therapy resistance has emphasized the importance of constant innovation in the field of anticancer drug development. Modern-day scientific advancements have made it possible to produce very specific medications that increase the effectiveness of treatments while minimizing side effects at the same time[8]. Moreover, the combination of various fields like precision medicine, computation, immunology, nanotechnology, and novel drug delivery systems is revolutionizing oncology. It makes it imperative to know about these modern-day developments to be able to design novel anticancer drugs in the coming days.

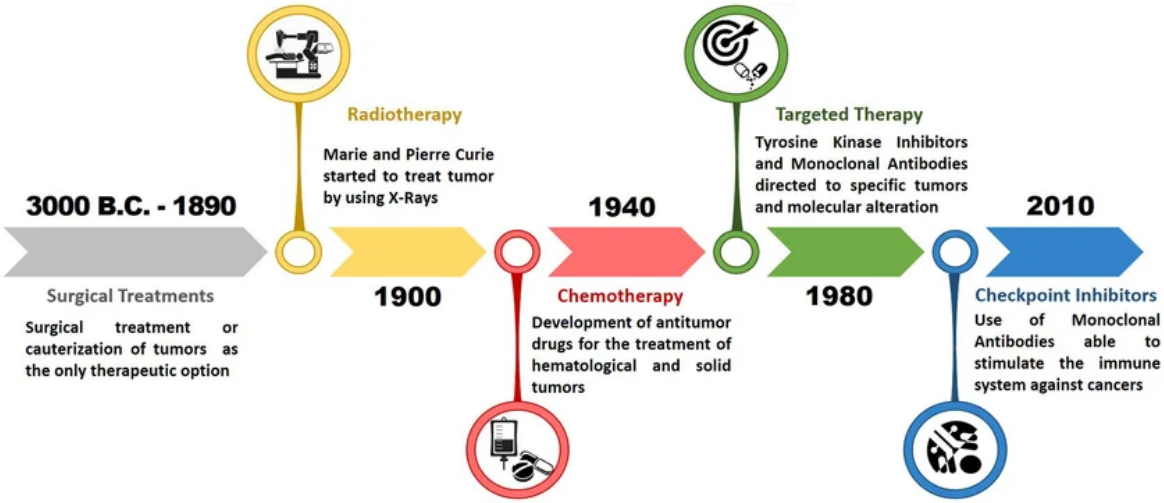

Figure 1. Evolution of Anticancer Therapeutic Strategies from Conventional Treatment to Precision Oncology

2. MOLECULARLY TARGETED AND PRECISION ANTICANCER DRUG DESIGN

The introduction of molecular targeted therapy in cancer treatment has been revolutionary in the sense that the focus has shifted from killing all dividing cells to targeting those components without which tumor cannot survive[9]. The strategy is based upon the identification of oncogene addiction, essential pathways, DNA repair defects, epigenetic addiction, or metabolic vulnerabilities distinguishing the cancerous cells from their normal counterparts. The developments in the field of medicinal chemistry and structural biology have yielded better inhibitors with better properties.

2.1 Small-Molecule Inhibitors and Structure-Guided Design

Small molecule inhibitors continue to play an essential role in anticancer drug discovery since they can cross the cell membrane and get access to intracellular proteins as well as be orally administered. Protein kinases are the best-known targets, and this is explained by their crucial role in signaling via phosphorylation and promoting cancer cell proliferation, survival, angiogenesis,

invasion, and evasion from immunity[10]. Selective inhibitors of BCR–ABL, EGFR, ALK, ROS1, BRAF, MEK, RET, MET, FGFR, BTK, FLT3, PI3K, and CDK4/6 have shown much success in clinic, especially when used in proper biomarker-selected patients.

Most recent approaches in the design of drugs have been developed to address the issues of resistance and poor selectivity seen in the first-generation drugs. Resistance can arise due to mutation in the drug binding site, up-regulation of the target gene, bypassing of the target signaling pathway, transformation of phenotype or enhanced drug efflux[11]. Therefore, second-generation inhibitors are developed such that they recognize mutated protein, bind regulatory pockets, inhibit various mutant types and still remain effective against modified protein conformation. Allosteric inhibitors bind to regions other than the common catalytic site while covalent inhibitors bind to a specific amino acid residue through a bond[12]. The development of inhibitors selective for mutants of KRAS shows that even undruggable proteins can be targeted through the recognition of transient or unrecognized binding pockets.

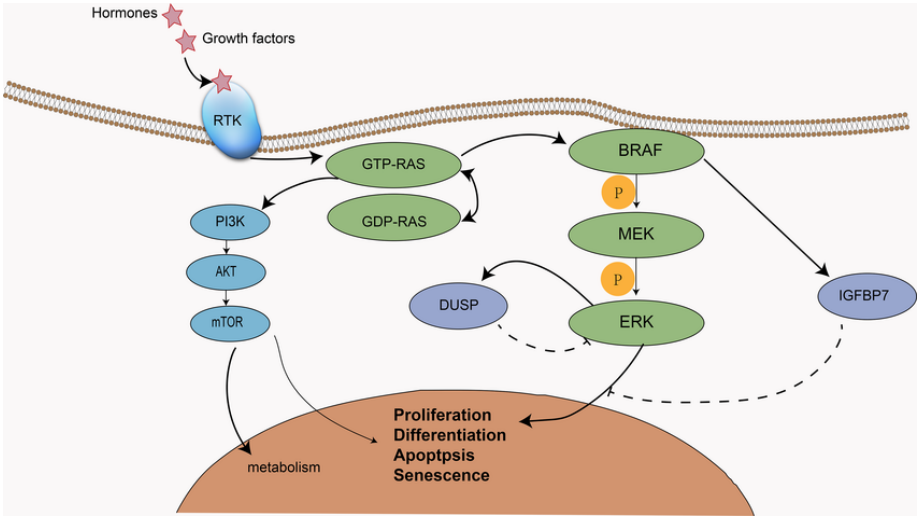

Figure 2. Major Oncogenic Signalling Pathways Targeted in Modern Anticancer Drug Discovery

Recent developments in the field of structural biology and computational modeling have made more targets available for use in anti-cancer drugs. The technologies used include fragment-based drug discovery, cryogenic electron microscopy, nuclear magnetic resonance spectroscopy, X-ray crystallography, and molecular dynamics simulations that can help scientists identify low-affinity chemical fragments and optimize them into highly effective therapeutic molecules. They are also useful in designing inhibitors of protein-protein interactions due to their wide but relatively flat binding interface[13]. There has been an increasing interest in targeting epigenetic modifiers such aDNA methyltransferases, histone deacetylases, bromodomain proteins, histone methyltransferases, and mutant metabolic enzymes because blocking them helps in restoring gene expression and cell differentiation. Nevertheless, proper regulation of selectivity, dose, and

duration is crucial since these modifiers are involved in performing normal cellular functions as well[14].

Table 1. Major Strategies in Contemporary Small-Molecule Anticancer Drug Design

Design Strategy	Mechanism	Advantage	Limitation
Orthosteric inhibition	Blocks the active site	Strong target inhibition	Limited selectivity
Allosteric inhibition	Binds a regulatory site	Better selectivity	Sites are difficult to identify
Covalent inhibition	Forms a stable target bond	Sustained potency	Off-target reactivity
Mutant-selective inhibition	Targets mutant proteins	Spares normal proteins	Further resistance mutations
Multi-target inhibition	Blocks multiple pathways	Reduces pathway escape	Higher toxicity risk
Protein–protein inhibition	Disrupts essential complexes	Targets difficult mechanisms	Broad binding surfaces
Epigenetic inhibition	Alters abnormal gene regulation	Restores drug sensitivity	Context-dependent toxicity

2.2 Precision Oncology, Biomarkers, and Synthetic Lethality

The concept of precision oncology is centered on personalized cancer therapy depending on the molecular signature of a particular tumor, not its localization. It uses methods of next-generation sequencing, gene expression profiling, immunohistochemistry, proteomics, and liquid biopsy to find clinically valuable biomarkers. Such biomarkers provide information for predicting a therapeutic effect, prognostication, resistance detection, and disease monitoring[15]. The importance of companion diagnostics is evident because some targeted drugs can be efficient only in the case of specific molecular changes in a patient. Molecular tumor boards use molecular and clinical data to select therapy.

Another important advance is tumour agnostic therapy, where the treatment depends on a common molecular alteration irrespective of the tissue type in which the tumour originated. Even though this method has widened the scope of precision medicine, there is still variation in treatment due to variations in tumour biology and microenvironment[16]. Another important approach is synthetic

lethality, which specifically targets cancer cells with preexisting genetic defects. The successful clinical application of PARP inhibitors in homologous recombination deficient cancers has proved to be an efficient model of precision drug discovery.

Present-day studies involve targeting the synthetic lethality approach for proteins involved in DNA damage repair, cell cycle control, metabolic pathways and chromatin remodelers using CRISPR-based screening, while liquid biopsy technologies have helped precision oncology through the detection of circulating tumor DNA, tumor cells and tumor RNA in blood samples[17]. The minimally invasive techniques help in stratification of patients, monitoring of treatment response, early detection of resistance and evaluation of minimal residual disease.

2.3 Resistance-Aware Combination Therapy and Tumour Microenvironment Targeting

Drug resistance continues to be one of the key problems of long-term success in cancer treatment. Drug resistance can be intrinsic – present even before the treatment or acquired during prolonged exposure to drugs due to genetic mutations, epigenetic changes, metabolism changes, efficient DNA repair, and protection by the tumour microenvironment. In order to overcome these obstacles, modern drug development tends to focus on resistance mechanisms at the stage of their emergence. Structural modelling, genomic and mutational analysis allow for prediction of the resistance mechanisms, and creation of inhibitors resistant to tumours' variations[18].

Rational combinations are becoming a significant approach to combatting drug resistance with simultaneous action on several cancer pathways. Rational combinations of targeted therapies with endocrine therapy, DNA repair inhibition, antiangiogenesis, epigenetic drugs, chemotherapy, and immunotherapies can have complementary and synergic effects, minimizing pathway reactivation. However, rational combinations need to be well-supported biologically since otherwise the combination may only increase toxicity.

The tumor microenvironment is also an important factor that influences the treatment outcomes. Elements like immune cells, fibroblasts, blood vessels, extracellular matrix, cytokines, and metabolic elements act as barriers to drug delivery and ensure the survival of tumors. As a result, new drug development focuses on anti-angiogenic treatments, tumor associated macrophages, immune suppression, and hypoxia-related signaling[19]. Moreover, alterations in glucose, lipid, amino-acid, and mitochondrial metabolism have also been identified as novel targets for drugs, despite the metabolic adaptability of cancers.

3. EMERGING THERAPEUTIC MODALITIES AND ADVANCED DELIVERY SYSTEMS

Modern anti-cancer drug discovery is not restricted to classical small molecule agents and non-conjugated monoclonal antibodies. Novel treatment strategies may enlist immune system cells, target delivery of toxic cargo, break down disease-causing proteins, alter gene expression, or

administer drugs under the influence of specific cancer-related factors[20]. Such technologies increase the diversity of possible target mechanisms but increase the complexity in their molecular construction, production, and clinical application.

3.1 Antibody–Drug Conjugates, Bispecific Antibodies, and Engineered Biologics

Antibody drug conjugates (ADCs) represent one of the most exciting innovations in cancer treatments today. They consist of a tumor-binding antibody, a linker molecule, and a cytotoxic agent that is effective at targeting cancer cells without damaging normal cells. Once the antigen binds, the ADCs enter the cell where the payload is released. The efficacy of the drug is influenced by factors like antigen choice, antibody affinity, stability of the linker molecule, payload potency, etc.

Some of the recent advancements in the development of ADCs are the use of stable and selective cleavable linkers, site-specific conjugation techniques, and cytotoxic payloads that include DNA damaging molecules and topoisomerase inhibitors[21]. These developments have led to better stability of drugs, pharmacokinetic properties, and tumour-specific delivery of the payload. However, despite these recent advancements, the main problems associated with ADCs are the heterogeneous antigen expression, premature drug release, drug resistance, inability to penetrate the solid tumours, and off-target effects. Therefore, the development of next generation ADCs is underway.

The bispecific antibodies are yet another category of engineered biologics with ability to bind two distinct antigens or epitopes at once. They can be either designed for recruiting T lymphocytes into tumour cells or may inhibit more than one signal transduction pathway or immune-targeting mechanisms. In addition to bispecific antibodies, there is a range of other engineered biologics including trispecific antibodies, immunocytokines, nanobodies, fusion proteins, and radioimmunopharmaceuticals that increase the list of therapeutic agents available for treatment of cancer[22]. Even though such advanced biologics have high specificity and multifunctionality, their structural complexity poses some problems.

Table 2. Emerging Antibody-Based Modalities in Anticancer Therapy

Modality	**Structural concept**	**Therapeutic function**	**Major challenge**
Monoclonal antibody	Single antigen-specific antibody	Blocks signalling or activates immune-mediated killing	Limited activity when antigen expression is heterogeneous

Antibody–drug conjugate	Antibody linked to a potent payload	Selectively delivers cytotoxic treatment	Linker stability, payload toxicity, and resistance
Bispecific T-cell engager	Binds tumour antigen and CD3	Redirects T cells towards malignant cells	Cytokine-release syndrome and antigen escape
Dual-pathway bispecific antibody	Recognises two signalling or immune targets	Simultaneously blocks complementary pathways	Complex dose and safety optimisation
Immunocytokine	Antibody fused to an immune cytokine	Concentrates immune stimulation in the tumour	Systemic inflammatory toxicity
Radioimmunoconjugate	Antibody carrying a radionuclide	Delivers targeted radiation	Dosimetry and damage to normal antigen-positive tissues
Antibody–protein degrader conjugate	Antibody transports a targeted degrader	Combines extracellular targeting with intracellular degradation	Delivery, internalisation, and release efficiency

3.2 Immunotherapy, Cancer Vaccines, and Cell- and Gene-Based Treatments

Immunotherapy has been an important aspect of modern cancer therapy due to the use of immune-checkpoint inhibitors for PD-1, PD-L1, and CTLA-4 pathways. In contrast to traditional anticancer therapies, immunotherapies do not kill tumour cells but instead try to stimulate the body's own immune response against the cancer. While numerous patients respond well, others have shown tumours resistant to immunotherapy treatment[23]. Recent efforts in science include research on other immune checkpoint targets and combination therapies with chemotherapy, radiotherapy, targeted treatments, and antiangiogenic agents.

Personalized cancer vaccines are also gaining traction as a potential option by using specific tumor neoantigens generated from genomic sequencing and analysis. The mRNA vaccine technology allows for fast generation and antigen selection and has the capacity to generate tumor-specific T-cell responses. These can potentially work even better if used in combination with immune checkpoint blockers or other immunotherapy agents.

Cell and gene therapy have greatly increased the treatment options for patients with advanced cancer. Some examples of such therapies include CAR-T cells, T cell receptors, tumour infiltrating lymphocytes, natural killer cells, gene editing methods, and gene therapy for restoration of tumour suppressors or silencing the oncogenes. In addition to these, there are oncolytic viruses which target only the cancerous cells but also promote antitumour immunity. Although promising results were obtained, particularly for hematologic cancers, these methods still encounter obstacles including delivery, heterogeneity of tumours, manufacturing complexity, immune-related toxicity, and low efficacy against many solid tumours[24].

3.3 Targeted Protein Degradation, Molecular Glues, and Nanomedicine

Targeted protein degradation has proven to be a novel approach for therapeutic intervention that differs from inhibitors because of its ability to remove harmful proteins from the body instead of just inhibiting their action. The most extensively investigated method of targeted protein degradation is PROTAC, a proteolysis-targeting chimera that targets the protein degradation apparatus of cells using an E3 ubiquitin ligase, ultimately resulting in the degradation of the target protein by proteasome[25]. This approach allows targeting of both enzyme and non-enzyme proteins and has already been used in androgen and estrogen receptors, kinases, transcription factors, and epigenetic regulators. Molecular glues have also been proposed as a simpler alternative type of protein degrader.

Despite all the potentials that these techniques hold, there are various hurdles associated with the targeted protein degradation techniques such as the low number of E3-ligases, poor cellular permeability, high molecular weight, tissue selectivity, and non-specific protein degradation. To counter these issues, the scientists have developed new E3-ligase recruiters, covalent and reversible degraders, trivalent PROTACs, tissue-specific degraders, light-activatable degraders, antibody-proteasome conjugates, and nanoparticle-mediated delivery systems[26]. These innovations are not only increasing the applications of induced proximity approach but also moving forward towards lysosomal degradation and autophagy.

Nanomedicine has also helped advance drug delivery for anticancer purposes through improved stability, solubility, circulation, tumor accumulation, and controlled release of drugs. Many types of nanocarriers, such as liposomes, polymer-based nanoparticles, lipid nanoparticles, dendrimers, and extracellular vesicles, have been studied for their efficacy in transporting chemotherapy, target drugs, nucleic acid drugs, and immunotherapy drugs. Current efforts in this area are geared towards developing actively targeted and stimulus-responsive nanocarriers for controlled drug release based on certain conditions in the tumor microenvironment, such as pH, hypoxia, enzymes, or reactive oxygen species[27]. Furthermore, drug delivery combined with imaging capabilities is being used to monitor drug delivery real-time. Nevertheless, the manufacture process, immune clearance, and lack of long-term safety still limit the use of nanomedicine for cancer treatments.

4. COMPUTATIONAL DISCOVERY, TRANSLATIONAL EVALUATION, AND CLINICAL DEVELOPMENT

The growing amounts of data relating to chemistry, structure, genomics, pharmacology, imaging, and the clinic present new possibilities for discovery of anticancer drugs through data analysis. Artificial intelligence and modelling can facilitate target identification, drug design, drug repositioning, toxicity prediction, biomarker selection, and clinical trial optimization. Simultaneously, patient-derived experimental models and adaptive clinical trials aim to strengthen the link between basic science and clinical practice.

4.1 Artificial Intelligence and Computer-Aided Anticancer Drug Design

There have been many advancements in cancer drug discovery through artificial intelligence (AI) and computer-aided drug discovery (CADD). There are several computational methods, including molecular docking, pharmacophore modelling, quantitative structure–activity relationship (QSAR) study, virtual screening, molecular-dynamics simulation, and de novo molecular design that can be used to discover the potential molecules without requiring experimental screening. This helps in improving the accuracy of predicting binding affinity, selectivity, and physiochemical properties of the compound.

Moreover, AI makes further use of these functions through the analysis of chemical and biological big data using machine and deep learning methods. They predict the activity of compounds, interactions, toxicity, pharmacokinetics, and interaction between drugs while providing functions like virtual screening, biomarker discovery, drug repurposing, and personalizing drug selection. While generative models of AI design new compounds that meet certain criteria for therapeutic function, reinforcement learning and multi-objective optimization find the right balance between potency, safety, and drug likeness in lead optimization.

However, despite all the developments described above, the efficiency of the artificial intelligence is highly dependent upon the quality and diversity of datasets used for their training. Noise in experimental observations, incomplete datasets and dataset bias may decrease the accuracy of the prediction and restrict the generalizability of AI algorithms[28]. This way, computational predictions should be tested experimentally in the laboratory and in clinical trials before being used for therapy. Instead of replacing medicinal chemists and pharmacologists, the artificial intelligence provides an excellent support tool in their work.

4.2 Multi-Omics, Advanced Screening, and Patient-Derived Models

Multi-omics techniques have revolutionized the field of cancer research by combining information about the genomics, transcriptomics, proteomics, epigenomics, metabolomics, and single-cell genomics to give an overall perspective about the tumour biology. It is very helpful in distinguishing between drivers and passengers and identifying patients that respond to specific

therapies and also in understanding the pathways associated with tumour development and therapy resistance. Moreover, single cell sequencing, spatial transcriptomics, and spatial proteomics offer important insights into tumour heterogeneity, immune cell interaction, metastasis, and tumour microenvironment influence on treatment response.

The advent of sophisticated screening techniques has contributed to the advancement of anticancer drugs discovery. The CRISPR technology can be used for the knockout, activation or modification of genes in order to study their significance, synthetic lethality, immunity evasion pathways as well as drug sensitivity factors. Chemical genetic screening can help to draw connections between the chemicals and biology, thus allowing the identification of new drug targets.

Experimental models derived from patients represent platforms that have greater clinical relevance when testing the efficacy of anticancer treatments. Three-dimensional tumour spheroids, patient-derived organoids, xenograft models, humanized mouse models, and tumour-on-chip technologies have greater accuracy than the traditional two-dimensional culture of cells in terms of replicating tumour structure, diversity of cells, and interaction with the microenvironment. These models can be used in drug testing, biomarker discovery, studying drug resistance, and treatment personalization[29]. Yet, because none of these models mimic human cancer completely, their combination is the best approach.

4.3 Clinical Translation, Regulation, and Innovative Trial Design

Successful translation of an anti-cancer drug involves demonstrating efficacy and safety. Even though major strides have been made in drug discovery, many drugs that fall into the category of oncology drugs end up being a failure during clinical development due to various factors like inadequate target validation, preclinical studies, safety concerns, poor patient selection, inadequate dosage regimes and poor clinical study designs. In an effort to increase the chances of success, many clinical trials that involve the use of biomarkers are currently using cancer patients whose tumors have a particular molecular alteration.

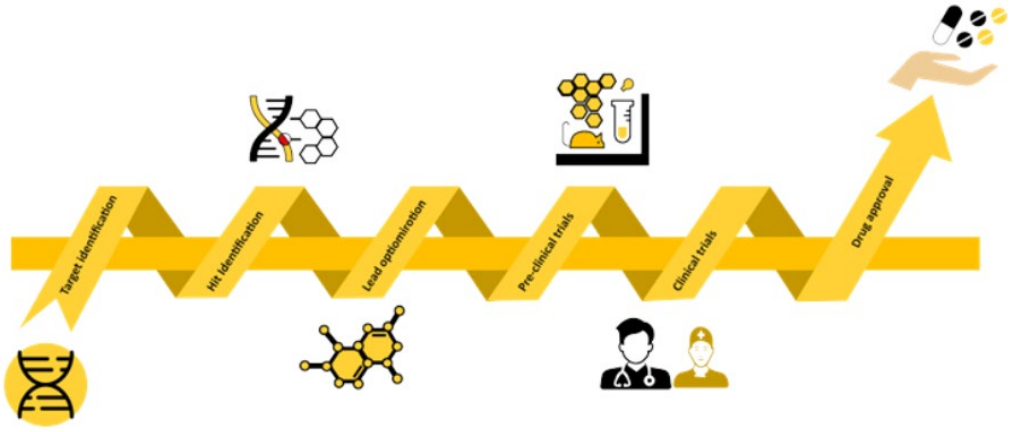

Figure 3. Workflow of the Anticancer Drug Discovery and Clinical Development Process

Clinical trials designed in an adaptive manner have also changed oncology studies since they can allow changes in treatment allocation, sample size, or arms of the study after intermediate results are obtained. The use of window of opportunity or neoadjuvant trials allows obtaining relevant data about the biological responses, treatment sensitivity, and tumor adaptation prior to final treatment. Furthermore, real-world data and external control groups are being used as supplements to conventional clinical trials; however, great care is needed when selecting data and ensuring methodological consistency. Dose optimization is another area emphasized in modern oncology trials[30].

The increasing complexity of contemporary anticancer treatments makes comprehensive regulatory assessment more important than ever. The complex nature of new therapies like ADCs, cell and gene therapies, immunotherapy and drug discovery assisted by AI requires a comprehensive evaluation of the quality of manufacture, stability of the drug, its immunogenicity, safety and monitoring after approval for commercialization. In addition, digital technologies like artificial intelligence, multi-omics profiling, CRISPR screening, patient-based models, liquid biopsy and drug-design software are increasingly used in target validation, biomarker identification and clinical decision making. Proper incorporation of digital technologies into the process of drug development should enhance translational efficiency.

Table 3. Comparative Analysis of Selected Studies on Recent Developments in Anticancer Drug Discovery and Design

Author(s) & Year	Study Focus	Major Findings	Research Gap / Limitation
Reis et al. (2017)[31]	Chromone scaffold in anticancer drug discovery	Demonstrated that chromone derivatives serve as versatile scaffolds with significant potential for developing selective anticancer agents through structural modification.	Limited clinical validation of many chromone derivatives, and optimization of pharmacokinetic properties remains necessary.
Sharma et al. (2017)[32]	Dendrimer nanoarchitectures for	Reported that dendrimer-based nanocarriers improve targeted drug delivery,	Clinical translation is constrained by manufacturing complexity,

	cancer diagnosis and drug delivery	imaging, and controlled release while reducing systemic toxicity.	long-term biocompatibility, and regulatory challenges.
Singh et al. (2016)[33]	Phytochemicals as leads for anticancer drug development	Identified numerous plant-derived compounds with promising anticancer activity against multiple molecular targets and signaling pathways.	Most phytochemicals require further optimization for bioavailability, standardization, and large-scale clinical evaluation.
Supuran (2017)[34]	Structure-based discovery of carbonic anhydrase inhibitors	Highlighted the effectiveness of structure-guided drug design in developing selective carbonic anhydrase inhibitors for cancer therapy.	Isoform selectivity, resistance mechanisms, and long-term therapeutic efficacy require additional investigation.
Szumilak et al. (2021)[35]	Hybrid drugs for overcoming anticancer drug resistance	Demonstrated that hybrid molecules targeting multiple pathways can improve therapeutic efficacy and reduce resistance development.	Limited clinical evidence and challenges in optimizing pharmacokinetics and toxicity profiles hinder widespread application.

5. DISCUSSION

The development of new cancer drugs using the advancements made in recent years has revolutionized the field of oncology as it has moved from traditional chemotherapeutic methods to a more precise and mechanistically based drug therapy[36]. This study reveals from its extensive literature review that advancement in the fields of medicinal chemistry, molecular biology, immunology, nanotechnology, and computational sciences has led to the development of new anticancer drugs which are more selective and efficient than the existing ones. Some of these innovations include targeted inhibitors, antibody–drug conjugates, immunotherapy, protein degraders, nanomedicine, artificial intelligence, and multi-omics approaches[37].

5.1 Interpretation and Analysis of Findings

The results show that the discovery process for current anticancer drugs is being driven by the principles of precision medicine and multi-disciplinary research. The methods of structure-based

drug design, therapy based on biomarkers, synthetic lethality and molecular targeting have contributed to the improvement of treatment specificity and efficacy[38]. Moreover, new methodologies such as antibody-drug conjugates, bispecific antibodies, immunotherapy, targeted protein degradation and nanomedicine have increased the range of treatment options[39].

5.2 Implications and Significance

The quick pace at which anti-cancer drug discovery is evolving means that there are major implications for drug research as well as clinical oncology. Drug design through computational means, diagnostic molecules, biomarkers-based treatment methods, and patient models have all become efficient in ensuring that drugs are developed and applied through precision medicine[40]. Novel platforms for treatment like immunotherapies, antibodies, and cellular and gene therapies as well as nanotechnology are providing fresh approaches to enhancing patient survival while minimizing the toxicity associated with treatment.

5.3 Research Gaps and Limitations

Although great progress has been made, there are still many issues that are holding back the development of novel anticancer treatments. Some of the most common obstacles include tumour heterogeneity, drug resistance, lack of validated biomarkers, preclinical model limitations, manufacturing difficulties, and high attrition rates in the clinic. Modern technologies, such as antibody-drug conjugates, protein degraders, gene-based therapeutics, and nanotechnology, also need to be investigated for safety and scale-up. Furthermore, this review is based on the published literature, and might not include some of the most recent industrial and clinical advances.

5.4 Future Research Directions

The future directions in this area should include the use of artificial intelligence, structural biology, multi-omics, and precision diagnostics to enhance anticancer drug discovery. It is important that focus should shift towards development of novel generation of antibody-drug conjugates, protein degraders, molecular glues, personalized vaccines against cancers, gene-editing approaches, and smart nanomaterials which can reverse the drug resistance. Improvement in the patient derived models, liquid biopsy, adaptive trials, and biomarker-driven therapies will enhance clinical translational success. Collaboration across disciplines will be critical in advancing safe and personalized anticancer therapies.

6. CONCLUSION

Recent developments in anticancer drug discovery and design have propelled the move away from conventional chemotherapy toward precision-based and targeted treatment modalities. The advancements made in molecularly targeted therapy, immunotherapy, antibody–drug conjugate technology, protein degradation technology, nanotechnology, artificial intelligence, and multi-

omics have facilitated target discovery and drug discovery. Nevertheless, barriers such as tumor heterogeneity, drug resistance, biomarker validation, manufacturing difficulties, and regulations still hinder the clinical translation process. It will be imperative for future success to use emerging technologies in conjunction with multidisciplinary efforts in developing safe, effective, and personalized anticancer drugs.

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