



Advances in Cancer Treatment: Innovative Strategies for Precision, Personalized, and Effective Cancer Care

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ABSTRACT

Introduction: Cancer remains a major global health challenge, and advances in molecular biology have progressively changed the approach to cancer treatment. Conventional modalities such as surgery, radiotherapy, chemotherapy, and endocrine therapy remain important, while precision oncology, targeted therapy, immunotherapy, cellular therapies, advanced drug-delivery systems, and artificial intelligence are increasingly influencing clinical decision-making. These developments have shifted cancer care from a primarily disease-based approach toward treatment strategies that consider tumor biology and individual patient characteristics.

Methods: A narrative literature review was conducted to summarize major advances in contemporary cancer treatment, with particular emphasis on precision oncology, molecular biomarkers, targeted therapy, immunotherapy, cellular and CAR-T cell therapy, cancer vaccines, nanotechnology-based drug delivery, artificial intelligence, personalized treatment, and mechanisms of treatment resistance. Relevant scientific and clinical literature was considered to provide an integrated overview of established treatment approaches and emerging therapeutic strategies.

Discussion: The reviewed literature highlights the increasing importance of molecular characterization in selecting appropriate therapies and identifying patients who may benefit from biomarker-guided treatment. Targeted therapies and immune-checkpoint inhibitors have expanded treatment options for selected malignancies, while CAR-T cell therapy and other cellular approaches have demonstrated substantial potential, particularly in hematological cancers. Cancer vaccines, bispecific antibodies, nanomedicine, liquid biopsy, and artificial intelligence represent additional areas of rapid development. Despite these advances, treatment resistance, tumor heterogeneity, treatment-related toxicity, high costs, infrastructure requirements, and unequal access to advanced diagnostic and therapeutic technologies remain important challenges.

Conclusion: Modern cancer treatment is increasingly becoming precise, personalized, multidisciplinary, and data-driven. Future progress will depend not only on developing innovative therapies but also on validating their clinical effectiveness, addressing resistance and long-term toxicity, improving affordability and accessibility, and integrating molecular information with conventional clinical assessment. A balanced combination of established and emerging treatment approaches may provide the most effective pathway toward individualized and equitable cancer care.

Keywords: Cancer; precision oncology; personalized medicine; targeted therapy; immunotherapy; chemotherapy; radiotherapy; CAR-T cells; biomarkers; artificial intelligence; precision medicine.

INTRODUCTION

Cancer is a group of diseases that involves an abnormal growth of cells, genomic instability, invasion of tissues and in many cases spreading to other parts of the body. While cancers vary greatly based on tissue of origin and molecular

characteristics, the shared commonalities in the biology of malignant transformation have enabled therapeutic strategies that are designed to selectively target tumor cell growth and/or survival. Surgery, radiotherapy, chemotherapy, endocrine therapy and a combination of these have traditionally been used to treat cancer. These are still basic methods because they are still effective in curing the disease, extending life, decreasing tumor size and controlling symptoms in many malignancies [1,2]. But traditional therapy can cause toxicity also in normal tissue and can have high short-term and long-term side effects.

However, molecular oncology has gradually altered this paradigm of therapy. In modern precision medicine, the aim is to use a patient's genetic, protein, molecular pathway and other biomarker information to determine the most beneficial treatment for an individual patient. Precision medicine is defined by the National Cancer Institute as an approach in which information about genes, proteins, environment, and lifestyle can help in the prevention, diagnosis or treatment of cancer [3]. Cancer precision medicine is the use of tumor characteristics to inform therapeutic decisions. However, the use of biomarker testing is gaining in importance especially for targeted therapies and immunotherapies which work effectively in patients whose tumours have particular molecular characteristics [4].

Precision oncology now includes targeted therapy as one of the key elements. Unlike more generic agents, which target rapidly dividing cells of any type, targeted agents are designed to inhibit or disrupt specific proteins or pathways that play a role in malignant growth, survival, angiogenesis or metastasis [5]. Secondly, immunotherapy has a new therapeutic principle, in which the patient's immune system is activated or re-directed to recognize and eradicate the malignant cells [7]. There have been durable responses in several cancers achieved with immune-based approaches such as immune-checkpoint inhibitors, monoclonal antibodies, adoptive cell therapies, and others [7-10].

This has led to a complex landscape of cancer treatments. These decisions can include: tumor stage, histological subtype, molecular changes, biomarker status, previous treatment, co-morbidities, performance status, patient preference, and treatment availability. This review aims at giving an overview of the current cancer treatments, with a particular focus on precision medicine, targeted therapy, immunology, cellular therapy, combinations of treatments, new technologies, problems, and prospects for the future.

Literature Search Strategy and Review Methodology

A narrative literature review was undertaken to summarize the major developments in cancer treatment, with particular emphasis on precision oncology, molecularly targeted therapies, immunotherapy, cellular therapies, emerging drug-delivery approaches, artificial intelligence, and personalized cancer care. The review approach was structured to provide a focused and transparent synthesis of the available literature while allowing the inclusion of both established evidence and emerging developments relevant to contemporary oncology.

Relevant literature was identified through searches of major biomedical and scientific databases, including PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The search strategy combined keywords and related terms such as “cancer treatment,” “precision oncology,” “personalized cancer therapy,” “targeted therapy,” “immunotherapy,” “immune checkpoint inhibitors,” “CAR-T cell therapy,” “cancer vaccines,” “antibody-drug conjugates,” “bispecific antibodies,” “nanomedicine,” “liquid biopsy,” “artificial intelligence,” and “treatment resistance.” Additional relevant publications were identified by examining the reference lists of key articles and review papers. [16]

Priority was given to peer-reviewed publications that provided clinically relevant or scientifically important information on the development, application, effectiveness, limitations, and future potential of cancer therapies. Recent literature was emphasized to reflect advances in rapidly evolving areas of oncology, while important earlier studies were retained when they represented landmark discoveries or established the basis for current treatment strategies.

The retrieved literature was assessed for relevance to the objectives and scope of the review. Publications that were unrelated to cancer treatment or did not contribute substantially to the topics covered were excluded from consideration. The selected literature was organized thematically rather than according to individual cancer types. The major themes included the evolution of cancer treatment, cancer biology and therapeutic targets, conventional treatment modalities, precision medicine, targeted therapy, immunotherapy, cellular and CAR-T therapies, cancer vaccines, nanotechnology-based drug delivery, artificial intelligence, personalized and multidisciplinary care, treatment resistance, global challenges, and future directions.

As this was a narrative review, the evidence was synthesized qualitatively rather than through quantitative meta-analysis or pooled statistical analysis. Particular attention was given to the clinical relevance of emerging treatment approaches, their potential advantages over conventional therapies, treatment-related limitations, mechanisms of resistance, accessibility, and the need for further clinical validation.

Evolution of Cancer Treatment

This evolution in the treatment of cancer is an evolution from anatomical and histological to more molecular and individual approaches. One of the earliest definitive treatments for solid tumors was surgery and it continues to be a critical treatment for localized disease where the tumor can be completely or almost completely removed. Radiotherapy was then an important method also for the control of localized and regional tumors, as a definitive therapy or as combined therapy with

surgery and systemic therapy. The advent of cytotoxic chemotherapy provided the means for systemic therapy to be used for disease outside of the head and neck, hematological malignancies and tumors showing high systemic chemosensitivity [1,2].

Hormonal manipulation then showed that certain tumors rely on endocrine signaling for their growth. Blocking pathways of hormone action was important in the context of breast and prostate cancers where this could significantly affect the course of the disease. Oncogenic drivers and molecular pathways then started the modern targeted therapy era. Agents that targeted molecular abnormalities showed that treatment could now be chosen based on the biology of the tumor and not just its anatomical location [5,6]. In more recent years, another great therapeutic paradigm has emerged, that of immunotherapy, which allows for immune cells to better recognize and destroy malignant cells [7–10].

However, this transformation has not superseded the traditional treatments. Rather, many new and well-known modalities are used in combination in modern oncology. Systemic therapy or radiotherapy following surgery may be used to lower the risk of recurrence; radiotherapy may be used alongside chemotherapy, endocrine therapy, targeted agents and/or immunotherapy; molecular testing may be used to identify patients who might benefit from specific targeted or immune-based treatments. Therefore, current cancer treatment should be considered a comprehensive treatment programme and not as an opposition between conventional and innovative treatments.

Cancer Biology and Therapeutic Targets

Cancer is a highly complex disease and understanding this is fundamental to understanding why the treatment varies from one cancer patient to another despite having similar cancers. Malignant cells can develop genetic and epigenetic changes to affect proliferation, apoptosis, DNA repair, metabolism, angiogenesis, invasion, and immune recognition. The changes can result in reliance on specific signaling pathways that eventually become targets for therapy. The molecular characterization has therefore become more and more relevant for the identification of actionable alterations and for the characterization of the biologically distinct tumor subgroups [3,6].

The microenvironment of cancer can also impact treatment success. Tumors are associated with immune cells, fibroblasts, endothelial cells, extracellular matrix molecules and signaling molecules. Other cancers create an immunosuppressive environment that restricts effective immune responses, and others have molecular features that make them more responsive to immune checkpoint inhibition [7]. Treatment is also complex due to the presence of multiple types of malignant cells in a tumor, known as tumour heterogeneity. Treatment can then kill the sensitive populations and leave resistant clones alive and growing.

Potential targets for therapeutic development include mutated kinases, receptor proteins, DNA-repair pathways, hormone receptors, angiogenic pathways, cell-cycle regulators, and immune-regulatory molecules. Their identification has been used to guide the development of small molecule inhibitors, monoclonal antibodies, antibody–drug conjugates and other targeted strategies [5,6]. Precision oncology thus relies on the ability to precisely classify the molecular profile of an individual's cancer.

Conventional Cancer Treatment

For most localized solid tumors, surgery is a mainstay of treatment. The main goal could be complete tumour removal, tumour reduction, preventing local complications or symptom palliation. The advent of minimally invasive surgery, robotics, image-guided surgery and reconstructive surgery has broadened the options for the patients who might be able to accomplish good tumor control with less morbidity. The decision for surgery is based on characteristics of the tumor, stage, anatomical relationships, fitness of the patient and availability of specialized expertise.

Radiation therapy is the application of ionizing radiation to destroy the DNA of the tumor cells and to slow cell growth. Three-dimensional conformal radiotherapy, intensity-modulated radiotherapy, image-guided radiotherapy, stereotactic radiotherapy and other techniques are the modern methods that are used to maximize the dose to the tumor and minimize dose to nearby normal tissues. Radiotherapy can be used as a pre-surgical treatment, post-surgical, as an up-front treatment, or for palliation. Improvements in imaging and treatment planning have increased the accuracy of delivering radiation.

Many cancers still use chemotherapy as an effective treatment as the chemotherapy drugs are effective systemically against the malignant cells. Chemotherapy is used as the main treatment in some types of cancer and may also be combined with some other treatments, such as surgery, radiation, endocrine therapy, targeted therapy, or immunotherapy [1,2]. But quickly dividing normal tissues, such as the bone marrow, gastrointestinal tract, mucous membranes, hair, and skin, may also be impacted, causing side effects such as a reduction in blood cells, gastrointestinal symptoms, mucous membrane injury, hair loss, and fatigue. Thus, the selection of treatment must take into account the expected benefit versus toxicity and patient-specific factors.

Endocrine therapy is especially significant in the treatment of hormone-sensitive cancers. Endocrine treatments stop the growth of certain breast and prostate cancers by blocking receptors, decreasing hormone levels, or interfering with how hormones work. These treatments can be used for early, advanced, or for long-term prevention of recurrence. Their effectiveness highlights the value of knowledge of the importance of specific biological pathways in the dependence of tumors.

Table 1. Conventional and Modern Approaches to Cancer Treatment

Treatment approach	Main principle	Major applications/role	Key advantages	Important limitations
Surgery	Physical removal or reduction of malignant tissue	Primarily localized and potentially resectable tumors; local control and palliation	Can provide definitive local tumor control; increasingly supported by minimally invasive and image-guided techniques	Limited in disseminated disease; depends on tumor anatomy, stage, patient fitness and specialist expertise
Radiotherapy	Delivery of ionizing radiation to damage tumor-cell DNA and inhibit tumor growth	Definitive, preoperative, postoperative, combined-modality treatment and palliation	Provides effective local/regional control and can be precisely planned to reduce exposure of surrounding tissues	Toxicity to normal tissues; access to advanced radiotherapy may be limited in resource-constrained settings
Chemotherapy	Systemic administration of cytotoxic drugs to eliminate or suppress malignant cells	Used as primary therapy in selected cancers and in combination with surgery, radiotherapy, endocrine, targeted or immune-based treatments	Systemic activity against malignant cells; useful for cancers with chemosensitivity	Non-selective effects on rapidly dividing normal tissues; adverse effects and treatment-related toxicity
Endocrine therapy	Blocking hormone receptors, reducing hormone levels or interfering with hormone signaling	Hormone-sensitive cancers, particularly breast and prostate cancers	Can provide prolonged disease control in hormone-dependent malignancies	Effective only when tumor growth is dependent on relevant endocrine pathways; resistance may develop
Targeted therapy	Inhibition of specific proteins, molecular abnormalities or signaling pathways involved in cancer growth and survival	Biomarker-selected cancers with actionable molecular alterations	Greater molecular selectivity than conventional cytotoxic therapy; supports precision oncology	Not all tumors have actionable targets; adverse effects, resistance and treatment cost remain concerns
Immunotherapy	Activation or restoration of anti-tumor immune responses	Several malignancies, particularly in patients with appropriate biological characteristics	Can produce durable responses in selected patients	Primary or acquired resistance; immune-related adverse events; predictive biomarkers are imperfect
Cellular therapy/CAR-T therapy	Use of selected or genetically modified immune cells to recognize and attack malignant cells	Particularly important in selected hematological malignancies	Highly personalized; can produce substantial responses in some relapsed or refractory cancers	Complex manufacturing, high cost, specialized care requirements and immune-related toxicities; challenges remain in solid tumors
Combination therapy	Integration of two or more therapeutic modalities with complementary mechanisms	Used across different stages and cancer types according to clinical and molecular characteristics	May improve disease control and reduce recurrence risk	Increased toxicity, complexity and cost; combinations require appropriate clinical evidence

Precision Medicine in Oncology

The molecular characterization of tumors has revolutionized the treatment of cancer, enabling the use of tumor characteristics in addition to anatomical classification. Tumor genomic testing can identify abnormalities in the genome, such as mutations, gene amplifications and deletions, rearrangements, and other abnormalities which may impact prognosis or treatment. Thus, biomarker assessment can help the clinician to diagnose patients who would be more likely to respond to specific targeted or immune-based treatments [3,4].

Cancer has been demonstrated to have similar molecular abnormalities in different organs and tumors in the same organ to have vastly different molecular profiles through the use of precision oncology. Breast, lung, colorectal and hematological cancers, for example, might possess molecularly subtyped subgroups that respond differently to therapy. Another emerging idea is Tumor-Agnostic Therapy: Some molecular characteristics may be used to identify patients who are candidates for some treatments regardless of the type of cancer [13]

Precision medicine is increasingly adopting new technologies, including next generation sequencing, comprehensive genomic Profiling, RNA analysis, protein biomarkers, and more. Furthermore, liquid biopsy has also been promising as a tool for the detection of circulating tumour DNA and for monitoring molecular changes with time. These technologies can aid in the detection of resistance earlier, choose effective treatments, and track the course of treatment without repeated invasive tumor sampling.

But precision medicine isn't a good universal treatment. Not all tumors have targetable mutations, mutations don't always predict treatments that are effective, and there's unequal access to broad genome testing. Moreover, molecular profiles of various regions of the same malignancy may be different due to the tumor's heterogeneity. Precision oncology should, therefore, be used in conjunction with the clinical exam, pathological evaluation, imaging, staging, and multidisciplinary decision making, and not as a stand-alone decision making system.

Table 2. Biomarkers and Molecular Characteristics Relevant to Precision Oncology

Molecular/biological characteristic	Role in precision oncology	Potential therapeutic relevance	Important consideration
Genetic mutations	Identify molecular abnormalities that may contribute to tumor growth and survival	May indicate the presence of an actionable therapeutic target	A detected mutation does not necessarily predict treatment response
Gene amplification or deletion	Characterizes genomic alterations within a tumor	May help identify biologically distinct tumor subgroups and potential therapeutic strategies	Clinical significance depends on the specific alteration and cancer context
Gene rearrangements	Detect structural genomic changes affecting cancer-related pathways	May provide a basis for molecularly guided treatment in selected cancers	Requires appropriate molecular testing and interpretation
Protein biomarkers	Provide information about tumor biology and therapeutic targets	May support selection of targeted or immune-based treatment	Biomarker performance varies between cancer types
PD-L1 expression	Provides information about the tumor immune environment	May contribute to selection of patients for immune-checkpoint-based approaches in selected settings	It is not a universally reliable predictor of benefit
Tumor mutational burden	Reflects the number of mutations present within a tumor	May contribute to assessment of potential sensitivity to immune-based treatment	Predictive value varies across tumor types and clinical contexts
Mismatch-repair status	Identifies defects in DNA mismatch-repair pathways	Can help identify tumors potentially responsive to immune-checkpoint inhibition	Requires validated testing and appropriate clinical interpretation
Microsatellite instability	Indicates genomic instability associated with defective mismatch repair	Can help identify selected patients who may benefit from immune-based treatment	Not all patients with MSI-related abnormalities respond identically
Circulating tumor DNA (ctDNA)	Provides a minimally invasive source of tumor-derived molecular information	May assist in monitoring molecular changes and treatment resistance over time	Clinical implementation and interpretation require appropriate validation
Tumor heterogeneity	Describes molecular differences among tumor-cell populations or tumor regions	Helps explain variable treatment response and emergence of resistant clones	A single tumor sample may not fully represent the molecular profile of the entire malignancy

Molecular profiling/next-generation sequencing	Provides broad characterization of genomic and other molecular abnormalities	Supports identification of potentially actionable alterations and treatment selection	Availability, cost, interpretation and access remain important limitations
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Targeted Therapy

One of the most significant advances in modern oncology is targeted therapy. These therapies block certain molecules or pathways that are vital for the survival and growth of cancer cells. Targeted therapy is defined by the National Cancer Institute as treatment that aims for proteins involved in the growth, division and spread of cancer cells, which is an important cornerstone of precision medicine [5]. There are two big groups of targeted treatments: small molecule inhibitors and monoclonal antibodies.

Examples of molecularly targeted therapy include kinase inhibitors. Therefore, abnormal kinase signals can stimulate proliferation without control, while blocking a particular kinase can inhibit the proliferation of a tumour. Monoclonal antibodies can bind receptors on the extracellular surface or other tumor-associated targets, thus interfering with receptor function, inducing immune-mediated destruction, or directly targeting and delivering cytotoxic compounds to the malignant cells [5,6]. Antibody-drug conjugates (ADC) are an important therapeutic platform that have the ability to target cells with antibodies and to carry potent cytotoxic drugs.

Targeted therapy might have more selective effects than standard cytotoxic therapy, however, it can still have toxic effects. Adverse effects can range depending on the target of the biological, such as dermatological reactions, gastrointestinal, hepatic, cardiovascular, hypertension, fatigue, and other organ specific reactions [5]. Acquired resistance is another big problem. Tumours can undergo genetic changes that make them resistant, or genetic change can activate alternative pathways to the suppressed one, change the way drugs are metabolised, or change in phenotype so they can survive treatment.

Combination targeted therapy to overcome resistance and suppress multiple pathways is being investigated with increasing frequency. However, combination therapies could result in more toxicity, treatment complexity, and cost. Thus, rational combination strategies should be well supported with biological rationale and trials of well-designed clinical trials.

Immunotherapy and Immune-Checkpoint Inhibition

Immunotherapy is a fundamentally new way to treat several types of cancer, relying on the patient's immune system. Tumors can escape from immune destruction in several ways: by decreasing the visibility of antigens, by secreting molecules that suppress the activity of immune cells, and by secreting molecules that inhibit immune-cell activity [7]. Some inhibitory pathways that suppress T-cell responses are inhibited by immune-checkpoint inhibitors, which reverse some of these mechanisms.

Programmed cell death protein 1 and its ligand, and cytotoxic T-lymphocyte-associated protein 4 are important checkpoint pathways. Blocking these pathways is a way to restore or reinvigorate the anti-tumor immune function in certain patients. Based on solid evidence of clinically significant responses in several cancers, immune checkpoint inhibitors have been proved to offer durable responses in certain malignancies [7,8]. Their success has stimulated much research in the area of predictive biomarkers and combination strategies.

Immune based treatment can result in immune-related adverse events, as the activated immune cells could also target normal tissues. Affected organs include the skin, gastrointestinal tract, liver, endocrine organs, lungs, kidneys, nervous system, and other tissues. Therefore, diagnosis and proper treatment is key to immunotherapy.

Checkpoint inhibitors do not work for everyone and primary or acquired resistance is a significant limitation. Response is affected by tumour mutational burden, mismatch-repair status, microsatellite instability, PD-L1 expression, tumour immune infiltration, and other factors, but none of these biomarkers is a reliable indicator of benefit in all cancers. Recent studies are thus aimed at pairing checkpoint inhibitors with other types of therapies such as targeting, chemotherapies, radiotherapies, vaccines, cellular therapy, and others [7-10].

Cellular Therapy and CAR-T Technology

Adoptive cellular therapy is a highly personalized treatment, in which immune cells are harvested from the patient or a donor, modified or selected outside the body, expanded (if necessary), and then introduced, to attack the malignant cells. Of these strategies, the chimeric antigen receptor T-cell, or CAR T therapy, has proven to be especially significant for certain haematological cancers [11,12].

CAR-T therapy requires isolation of T cells, genetic engineering of the cells to express the chimeric antigen receptor, expansion of the modified T cells and reintroduction of those cells into the patient. By engineering a receptor to recognize a specific antigen, T cells can be directed to an antigen expressed on a malignant cell to launch a cytotoxic immune response against that cell [11]. In some patients with relapsed or refractory blood cancer, this technology has yielded spectacular results.

CAR-T therapy has great promise in the clinic, although there are some drawbacks. Specialized clinical management is necessary for cytokine release syndrome, immune effector cell-associated neurotoxicity syndrome, prolonged cytopenias, infections and other complications. The manufacturing process is complex, treatment is expensive and many areas lack access. Moreover, the efficacy obtained in hematological malignancies has not been uniformly achieved in solid tumors, primarily due to the antigen heterogeneity, the barriers to tumor penetration, the immunosuppressive micro-environment and other biological challenges [11,12].

Current research is exploring next generation CAR designs, dual targeting strategies, armored CAR-T cells, allogeneic cellular CARs, natural killer-cell therapy, tumor-infiltrating lymphocytes, and combination with checkpoint inhibitors. These advancements will broaden cellular immunotherapy's potential applications for treating cancer.

Cancer Vaccines and Emerging Immunotherapeutic Strategies

Another strategy for inducing tumor-specific immune responses is through cancer vaccines. Therapeutic cancer vaccines are designed to boost the immune system in the presence of a cancer. Therapeutic cancer vaccines are intended to improve immunity to an existing cancer, in contrast to preemptive vaccines for oncogenic infections. Tumor-associated antigens, tumor-specific neoantigens, dendritic-cell approaches, messenger RNA technologies and personalized vaccine platforms are being studied.

Neoantigen vaccines are especially promising as they can potentially be made against mutations that are unique to tumors and not present in normal cells. The identification of neoantigens has been greatly aided by recent improvements in sequencing and computational prediction. Thus, personalized vaccine development can be used in addition to precision oncology and develop an immune response specific to an individual tumor.

Another emerging class of immunotherapeutics that are currently very much in the forefront of research are bispecific antibodies. These molecules are able to bind to both immune-cell targets as well as to the antigens of the malignant cells, thereby positioning immune effector cells in the vicinity of cancer cells. They have the potential to shift immune activity, which offers potential for treating hard-to-control diseases with conventional antibodies.

Extensive research is ongoing for combination immunotherapy. Checkpoint inhibitors can be used with other therapies, including radio-, chemo-, targeted therapy, antiangiogenic agents, vaccines or cellular therapy. The ultimate goal is to break through immune suppression, disrupt the release of tumor antigens, boost infiltration of immune cells, or prevent tumor resistance. However, combination therapies need to be carefully tested as stimulation of the immune system can lead to toxicity as well.

Drug Delivery and Nanotechnology in Cancer Treatment

New drug-delivery systems aim to increase therapeutic activity with a decrease in systemic toxicity. Significant interest has been shown in nanotechnology due to the potential for nanoparticles to enhance the solubility, stability, circulation time, tumor accumulation and controlled release of drugs. Different systems such as liposomes, polymeric nanoparticles, lipid nanoparticles, dendrimers, nanogels and other systems have been studied with the aim of using them as anticancer agents.

The theoretical benefits of nanomedicine are the enhanced delivery of cytotoxic drugs to tumors, prevention of premature degradation of therapeutic molecules and the addition of targeting ligands. A second approach might involve the use of nanoparticles to carry more than one therapeutic agent, which would facilitate combination treatment. Biological barriers and variable tumor vascularization and drug distribution, immune clearance, manufacturing constraints, and regulatory hurdles are, however, important factors.

Combination of nanotechnology with precision oncology could be an increasingly useful approach. Theoretically, molecular profiling can be used to identify tumor types with specific receptors or molecular features, and engineered delivery systems can be developed to selectively target therapeutic payloads to those tumor types. Additional clinical testing will be needed to identify the nanotherapeutic strategies that prove to be meaningful enhancements to existing therapies.

Artificial Intelligence and Digital Technologies in Oncology

AI has now made its way into the cancer diagnosis, treatment planning, drug discovery, prognosis and clinical decision support. Machine-learning algorithms can be used to analyze large sets of information from pathology, radiology, genomics, electronic health records and clinical trials. In imaging, AI could help identify, segment, classify, and monitor the response to treatment of tumors.

Another emerging field of great potential is digital pathology. Analysis of the histopathology images by computer may be able to detect the morphological patterns that are not very easy to quantify even from conventional histopathology. The potential for digital pathology to be integrated with molecular data might assist in the identification of relationships between the tumor morphology, genotype, prognosis and treatment response.

AI could also aid in drug development through the identification of prospective therapeutic targets, forecasting molecular interactions, drug screening of potential compounds, and the analysis of clinical-trial data. But, AI systems need a high-quality representative data set and validation. Bias, data privacy, interpretability, cybersecurity, and an inappropriate reliance on algorithmic predictions are still critical issues.

But the future of AI should be seen as a support rather than a substitute for oncologists, pathologists, radiologists, surgeons, pharmacists and other health care workers. Systems most likely to be useful are probably those that are part of multidisciplinary systems and subjected to a prospective clinical evaluation.

Table 3. Emerging Technologies and Strategies in Modern Cancer Care

Emerging strategy	Basic approach	Potential contribution to cancer care	Current challenges
Cancer vaccines	Stimulate immune responses against tumor-associated or tumor-specific antigens	May enhance tumor-specific immunity and complement other immunotherapeutic approaches	Identification of appropriate antigens, variable immune responses and need for further clinical validation
Personalized neoantigen vaccines	Target tumor-specific mutations identified through molecular and computational analysis	Offers the possibility of individualized immune responses against a patient's tumor	Requires sequencing, neoantigen prediction, individualized manufacturing and clinical validation
mRNA-based vaccine approaches	Use messenger RNA technology to stimulate antigen-specific immune responses	Provides a flexible platform for development of personalized cancer vaccines	Optimization, delivery, manufacturing and demonstration of durable clinical benefit
Bispecific antibodies	Simultaneously bind immune-cell targets and malignant-cell antigens	Can bring immune effector cells into close proximity to cancer cells	Toxicity, appropriate target selection and resistance require continued evaluation
Nanomedicine and nanoparticles	Use nanoscale carriers to transport therapeutic agents	May improve drug solubility, stability, circulation, tumor accumulation and controlled release	Biological barriers, variable tumor distribution, immune clearance, manufacturing and regulatory issues
Lipid nanoparticles and related delivery systems	Encapsulate therapeutic molecules within specialized delivery systems	May facilitate delivery of therapeutic payloads and support combination strategies	Delivery efficiency, biological distribution, manufacturing and regulatory requirements
Artificial intelligence (AI)	Applies computational and machine-learning approaches to large clinical and biological datasets	Potential applications include imaging, pathology, prognosis, drug discovery and clinical decision support	Data quality, bias, privacy, interpretability, cybersecurity and need for clinical validation
Digital pathology	Computer-assisted analysis of histopathological images	May identify morphological patterns and integrate pathological findings with molecular information	Standardization, validation, data quality and integration into clinical workflows
Liquid biopsy	Analysis of circulating tumor-derived material, including ctDNA	May support molecular monitoring and earlier identification of treatment-related changes or resistant clones	Sensitivity, interpretation, standardization and clinical validation
Next-generation cellular therapies	Development of advanced CAR designs, dual-targeting strategies, allogeneic approaches, natural killer-cell therapies and tumor-infiltrating lymphocytes	May expand the potential applications of cellular immunotherapy	Manufacturing complexity, safety, tumor heterogeneity and limited efficacy in some solid tumors
Multidisciplinary precision cancer care	Integration of molecular data with pathology, imaging, clinical assessment and patient factors	Supports individualized treatment selection and coordinated cancer management	Requires multidisciplinary expertise, infrastructure, molecular testing and equitable access

Personalized Treatment and Multidisciplinary Cancer Care

Genomic testing is not the only aspect of personalized cancer treatment. Tumor biology, stage, age, comorbidities, functional status, previous treatment, and psychosocial factors, patient preferences, and expected quality of life should all be taken into consideration in individualized care. Two patients with the same histology can then be treated differently for cancer.

Tumor boards may be multidisciplinary and include medical oncology, radiation oncology, surgery, pathology, radiology, molecular diagnostics, nursing, pharmacy, nutrition, rehabilitation and palliative care. This is especially significant for cancer that may need multiple or sequential treatments.

The need for patient-centered decision making is also critical. Treatment must take into account response to therapy, survival, treatment burden and functional outcomes, fertility, psychosocial wellbeing, financial toxicity and patient goals. Shared decision making enables clinicians to discuss the treatment benefits, uncertainties, risks and options.

Supportive and palliative care should not be associated with end-of-life situations. Management of symptoms, nutrition support, psychological support, pain management, rehabilitation and the management of side effects of treatment can be integrated into the cancer journey. Comprehensive cancer care is about prolonging life and keeping people's dignity and quality of life intact.

Treatment Resistance and Disease Recurrence

There is a significant resistance to the treatment of cancer. Resistance can occur prior to treatment or during treatment. The mechanisms involved include genetic mutations, activation of other signaling pathways, changes in drug metabolism, alteration in DNA repair, tumour cell plasticity, immune escape, resistance selection.

The molecular evolution of targeted therapies is especially susceptible because tumors can develop secondary mutations that will not bind to the drug or activate alternate pathways. Immune resistance can be due to suboptimal antigen presentation, immune exclusion, immunosuppressive tumor microenvironments, or altered interferon signaling. Resistance to chemotherapy can be developed due to drug efflux, change in apoptosis, increased DNA repair, and metabolic adaptation.

So, it is becoming more and more crucial to watch for therapeutic benefits. While conventional imaging is still valuable, there may be more molecular information available from circulating tumour DNA and other liquid biopsies. Serial molecular testing may have a role to play in detecting resistant clones before radiological progression is noted.

Overcoming resistance will probably require adaptive treatment strategies. These can be sequential targeted therapy, rational drug combinations, combinations based on immunity, interruption or modification of therapy in some cases and individual monitoring. Future clinical trials should focus more on the efficacy of a treatment as well as the development of resistance and how this resistance can be prevented or delayed.

Global Challenges in Cancer Treatment

Although significant treatment progress has been achieved, there is a great disparity in access to effective cancer treatment globally. In a resource-poor environment, patients may be delayed in receiving timely diagnosis, limited access to pathology and molecular testing, scarcity of oncology specialists, inadequate radiotherapy facilities, lack of essential medicines and financial barriers. Thus, achievement and discovery of scientific progress is not producing a more equitable cancer outcomes.

Other challenges involve the cost of some of the specific drugs, molecular testing and cellular therapy and advanced immunotherapies. Beyond the clinical effectiveness, there are also questions of cost-effectiveness, infrastructure, staff capacity and sustainability. Precision medicine can be challenging especially if genomic testing and advanced treatments are limited to a fraction of patients.

A worldwide perspective is therefore needed which is adapted to local resources in the oncology field. A crucial role in prevention, vaccinations for oncogenic infections, screening, early diagnosis, pathology services, essential surgeries, radiotherapy, chemotherapy, pain management and palliatives remains very crucial. Basic cancer treatment needs must be maintained and advanced precision treatments must be used too.

International cooperation is useful in areas of technology transfer, development of clinical research capacity, development of standard clinical guidelines, data sharing, and development of affordable therapeutic strategies. Innovation and accessibility then, should be the future of cancer treatment.

CONCLUSION

Treatment of cancer in the future will be more precise, personalized, integrated and data-driven. These technologies are collectively transforming oncology: molecular profiling, liquid biopsy, artificial intelligence, advanced imaging, digital pathology, precision immunotherapy, and cellular therapy, nanomedicine, as well as innovative drug delivery technologies. There is increasing recognition of the value of identifying actionable molecular abnormalities – targeted therapy – and the value of transforming the patient's immune system as a potent therapeutic mechanism – immunotherapy – [5–11]. Precision

immunotherapy and cellular treatment continues to develop in recent years to find ways around resistance and advance treatment to more hard-to-treat malignancies [14,15]

However, clinical validation is an important aspect of any innovation. Patients don't necessarily benefit from the discovery of a molecular target or a prediction by computer, as they must benefit from the resulting treatments. Future studies should thus focus on optimal clinical trials, real world effectiveness, longterm toxicities, quality of life, cost effectiveness, equity and patient centered measures. Precision medicine will also be used in conjunction with conventional oncology, not instead of it, as long as the latter continues to be very effective.

The best approach to cancer care is most likely a mix of early detection, precise diagnosis of the pathology, detailed molecular analysis, informed surgical and radio-therapy, rational system treatment, targeted therapy, immunotherapy, cellular therapy, supportive treatment, rehabilitation and ongoing monitoring. Not only should the goal be to create more treatments, it must also be to define which treatment, for which patient, at which stage, in what combination, and for how long. This can lead to a shift in cancer treatment from a disease-based system to a truly personalized system of care.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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