

EMERGING ROLE OF PRECISION ONCOLOGY IN THE MANAGEMENT OF SOLID TUMORS

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Abstract

The management of solid tumors has seen profound advancements over the last few decades, primarily driven by the rise of precision oncology. This paradigm shift focuses on tailoring cancer treatments based on individual molecular and genetic profiles, improving treatment outcomes, reducing side effects, and enhancing survival rates. This article examines the principles and application of precision oncology in managing solid tumors, detailing cutting-edge diagnostic techniques, therapeutic strategies, and clinical outcomes. Additionally, we explore the challenges in the field, including tumor heterogeneity, therapeutic resistance, and the need for greater healthcare access. The integration of precision oncology into clinical practice, along with collaborative research, is critical to overcoming these obstacles and realizing the full potential of this innovative approach. Building on this foundation, ongoing advances in high-throughput sequencing, bioinformatics, and artificial intelligence are further refining the ability to identify actionable biomarkers and predict therapeutic responses with greater accuracy. Multidisciplinary tumor boards and molecular profiling programs are increasingly guiding clinical decision-making, ensuring that genomic data are translated into personalized treatment plans. Moreover, the growing role of real-world evidence, adaptive clinical trials, and combination therapies is accelerating the development of more effective and durable treatment strategies. As precision oncology continues to evolve, its success will depend not only on technological innovation but also on ethical implementation, cost-effectiveness, and equitable access, ultimately shaping a more patient-centered and data-driven future for solid tumor management.

Keywords: Precision oncology, Solid tumors, Molecular profiling, Targeted therapy, Cancer management, Genomics, Immunotherapy.

Introduction

Cancer remains one of the leading causes of death worldwide, with solid tumors representing most of the cancer-related mortality. Traditional treatments such as surgery, chemotherapy, and radiation have been the cornerstone of cancer therapy for decades. However, these approaches often lack specificity and are associated with significant adverse effects, limiting their overall effectiveness and patient quality of life. Over the past two decades, the advent of precision oncology — a treatment approach based on the genetic and molecular profile of an individual's tumor — has revolutionized cancer care. This shift from a generalized to a personalized approach promises to

deliver more effective therapies with fewer side effects. The term "precision oncology" encompasses the use of diagnostic tools to analyze the molecular and genetic makeup of tumors, enabling the development of targeted therapies. These therapies aim to block specific molecules or pathways responsible for tumor growth, offering a more refined and tailored approach compared to conventional treatments. As the field continues to evolve, it brings new hope to patients with cancers that were previously difficult to treat, particularly those with advanced-stage or refractory solid tumors.

The Genetic Foundations of Cancer

Cancer is fundamentally a genetic disease arising from the accumulation of alterations in a cell's DNA that

disrupt normal regulatory mechanisms controlling growth, differentiation, and survival. These genetic changes may be inherited (germline mutations) or acquired over an individual's lifetime (somatic mutations) because of environmental exposures, lifestyle factors, aging, or random errors during DNA replication. When critical genes that regulate the cell cycle, DNA repair, or programmed cell death are affected, cells may gain a selective growth advantage, leading to uncontrolled proliferation and tumor formation.

At the core of cancer genetics are mutations in three major classes of genes: oncogenes, tumor suppressor genes, and DNA repair genes. Oncogenes, such as KRAS, EGFR, and BRAF, promote cell growth and survival when abnormally activated. In contrast, tumor suppressor genes, including TP53, RB1, and BRCA1/2, normally act as cellular "brakes" that inhibit uncontrolled division or trigger apoptosis; their inactivation removes these protective barriers. Defects in DNA repair genes further exacerbate genomic instability, allowing mutations to accumulate at an accelerated rate and driving cancer progression.

Beyond single-gene mutations, cancer development is also shaped by complex genomic and epigenetic alterations. Chromosomal rearrangements, copy number variations, and aneuploidy can profoundly alter gene expression patterns, while epigenetic modifications such as DNA methylation and histone modification influence which genes are turned on or off without changing the underlying DNA sequence. Together, these genetic and epigenetic events contribute to tumor heterogeneity, a hallmark of solid tumors that underlies variable treatment responses and the emergence of drug resistance.

Understanding the genetic foundations of cancer has been pivotal to the evolution of precision oncology. By identifying specific molecular alterations that drive tumor behavior, clinicians can stratify patients, predict prognosis, and select targeted therapies tailored to an individual's tumor profile. This genetic insight not only enhances therapeutic efficacy but also provides a framework for early detection, risk assessment, and the development of novel, more personalized cancer treatments.

Tumor Heterogeneity and Its Impact

Tumor heterogeneity refers to the presence of diverse cellular, genetic, and phenotypic characteristics within a single tumor (intra-tumoral heterogeneity) as well as between tumors of the same histological type across different patients (inter-tumoral heterogeneity). This diversity arises from the continuous accumulation of genetic

mutations, epigenetic alterations, and adaptive responses to the tumor microenvironment. As cancer cells evolve under selective pressures such as immune surveillance and therapeutic interventions, distinct subclonal populations emerge, each with unique biological behaviors and clinical implications.

Intra-tumoral heterogeneity plays a critical role in disease progression and treatment resistance. While targeted therapies may effectively eliminate dominant tumor clones, smaller subpopulations harboring resistant mutations can survive and expand, leading to relapse or disease progression. This dynamic evolution challenges the effectiveness of single-agent therapies and underscores the need for combination treatments and adaptive therapeutic strategies that can address multiple tumor subclones simultaneously.

Inter-tumoral heterogeneity further complicates cancer management, as tumors that appear similar under histopathological examination may have markedly different molecular drivers and clinical outcomes. For example, two patients with the same type of solid tumor may respond differently to identical treatments due to distinct genetic alterations or signaling pathway dependencies. This variability highlights the limitations of traditional "one-size-fits-all" treatment approaches and reinforces the importance of comprehensive molecular profiling in guiding precision oncology.

The impact of tumor heterogeneity extends beyond therapeutic response to influence prognosis, metastatic potential, and immune interactions. Heterogeneous tumors are often more aggressive and adaptable, capable of evading immune detection and colonizing distant organs. Addressing tumor heterogeneity requires integrative approaches that combine genomics, transcriptomics, and spatial analysis, along with longitudinal monitoring through liquid biopsies. Such strategies are essential for developing more durable, personalized treatment regimens and improving long-term outcomes in patients with solid tumors.

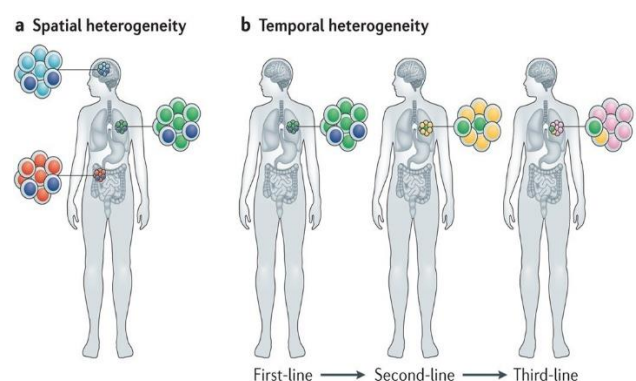


Figure 1: Tumor heterogeneity

Next-Generation Sequencing (NGS)

NGS has revolutionized cancer genomics, allowing clinicians to obtain detailed molecular profiles of tumors. This technology can sequence entire genomes, exomes, or specific genes of interest to identify mutations that may be targeted by existing therapies or clinical trials. NGS also enables the detection of rare mutations, which are often missed by traditional diagnostic methods. NGS supports the identification of tumor heterogeneity and clonal evolution, providing insights into disease progression and mechanisms of treatment resistance. The integration of NGS results into clinical workflows facilitates personalized treatment selection and improved prognostic assessment. As sequencing costs continue to decline, NGS is expected to become increasingly accessible and central to precision oncology practice.

Liquid Biopsy

Liquid biopsy is an innovative, minimally invasive diagnostic approach that enables the detection and analysis of tumor-derived biomarkers in body fluids, most commonly blood. Unlike traditional tissue biopsies, which are invasive and provide only a snapshot of a single tumor region at a specific time point, liquid biopsies offer a dynamic and comprehensive view of tumor biology. They capture circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), exosomes, and other tumor-associated molecules, making them particularly valuable in the context of precision oncology for solid tumors.

One of the key advantages of liquid biopsy is its ability to reflect tumor heterogeneity and temporal evolution. As tumors grow, metastasize, or respond to therapy, they continuously shed genetic material into the bloodstream. Analysis of ctDNA allows clinicians to identify actionable mutations, monitor treatment response in real time, and detect minimal residual disease or early relapse before it becomes clinically apparent on imaging. This real-time monitoring capability is especially important for understanding mechanisms of therapeutic resistance and guiding timely modifications in treatment strategies.

Liquid biopsy also plays an increasingly important role in early cancer detection and risk stratification. Advances in ultra-sensitive sequencing technologies have improved the ability to detect low levels of tumor-derived DNA, opening new possibilities for

cancer screening and surveillance in high-risk populations. In patients where tissue biopsy is not feasible due to tumor location or poor clinical condition, liquid biopsy provides a safer and more accessible alternative for molecular profiling.

Despite its promise, several challenges limit the widespread clinical implementation of liquid biopsy. These include variability in assay sensitivity, standardization of testing platforms, and interpretation of low-frequency variants. Additionally, not all tumors shed sufficient biomarkers into circulation, which may reduce detection accuracy. Ongoing research, technological refinement, and integration with other diagnostic modalities are essential to fully harness the potential of liquid biopsy as a cornerstone of precision oncology in solid tumor management.

Molecular Imaging

Molecular imaging is a powerful diagnostic modality that enables the visualization, characterization, and quantification of biological processes at the molecular and cellular levels within living organisms. Unlike conventional imaging techniques that primarily depict anatomical structures, molecular imaging provides functional and biochemical information about tumor behavior, including metabolism, receptor expression, hypoxia, and cellular proliferation. In the context of precision oncology, molecular imaging plays a crucial role in diagnosing solid tumors, guiding treatment selection, and monitoring therapeutic response.

Techniques such as positron emission tomography (PET), single-photon emission computed tomography (SPECT), and hybrid imaging systems like PET/CT and PET/MRI utilize targeted radiotracers to detect specific molecular pathways involved in cancer progression. For example, ¹⁸F-fluorodeoxyglucose (FDG) PET exploits the increased glucose metabolism of cancer cells, while newer tracers target hormone receptors, amino acid transporters, or immune checkpoints. These approaches enable more accurate tumor staging, identification of metastatic lesions, and differentiation between viable tumor tissue and post-treatment changes.

Molecular imaging also contributes significantly to treatment planning and response assessment. By noninvasively evaluating target expression and pathway activity, clinicians can predict which patients are most likely to benefit from targeted therapies or immunotherapies. Furthermore, serial imaging allows

early assessment of therapeutic efficacy, often before changes in tumor size become evident, facilitating timely treatment modification and reducing unnecessary toxicity.

Despite its advantages, molecular imaging faces challenges related to tracer availability, cost, radiation exposure, and standardization across clinical settings. Continued development of novel, highly specific imaging probes and integration with genomic and proteomic data are expected to enhance its precision and clinical utility. As these technologies evolve, molecular imaging will remain an essential component of personalized cancer care, bridging the gap between molecular diagnostics and real-time clinical decision-making in solid tumor management.

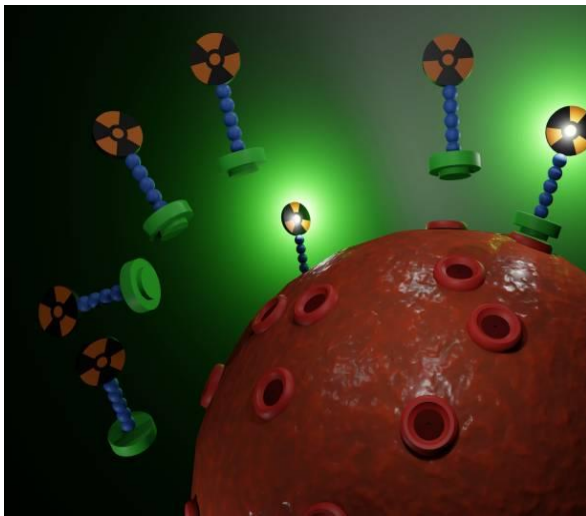


Figure 2: Molecular imaging

Targeted Therapies

Targeted therapies represent a cornerstone of precision oncology, designed to specifically inhibit molecular pathways and genetic alterations that drive tumor growth and survival. Unlike conventional chemotherapy, which non-selectively affects rapidly dividing cells, targeted agents act on defined oncogenic targets such as mutated proteins, overexpressed receptors, or dysregulated signaling cascades. This selective mechanism improves therapeutic efficacy while minimizing damage to normal tissues, thereby reducing treatment-related toxicity.

Several classes of targeted therapies have transformed the management of solid tumors. Small-molecule inhibitors, such as tyrosine kinase inhibitors (TKIs), block intracellular signaling

pathways critical for cancer cell proliferation and angiogenesis. Examples include EGFR inhibitors in non-small cell lung cancer, BRAF inhibitors in melanoma, and HER2-directed therapies in breast and gastric cancers. Monoclonal antibodies, on the other hand, target extracellular receptors or ligands, interfere with tumor–host interactions, and may also activate immune-mediated tumor destruction.

The clinical success of targeted therapies relies heavily on accurate molecular profiling to identify patients most likely to benefit. Biomarker-driven treatment selection has led to significant improvements in response rates and progression-free survival in multiple solid tumors. However, the development of acquired resistance—often due to secondary mutations, pathway bypass mechanisms, or tumor heterogeneity—remains a major limitation. To address this, combination strategies integrating multiple targeted agents or pairing targeted therapy with chemotherapy, immunotherapy, or radiotherapy are increasingly being explored.

Overall, targeted therapies have redefined cancer treatment paradigms by shifting the focus from tumor location to tumor biology. Continued advances in genomics, drug development, and resistance monitoring are expected to expand the range of actionable targets and improve long-term outcomes, reinforcing the central role of targeted therapies in the personalized management of solid tumors.

Immunotherapy

Immunotherapy has emerged as a transformative approach in the treatment of solid tumors by harnessing the patient's own immune system to recognize and eliminate cancer cells. Under normal conditions, the immune system can detect and destroy abnormal cells; however, cancer cells often evade immune surveillance through various suppressive mechanisms. Immunotherapeutic strategies aim to overcome these barriers, restoring or enhancing anti-tumor immune responses and achieving durable clinical benefits in a subset of patients.

Among the most successful immunotherapeutic modalities are immune checkpoint inhibitors, which target regulatory pathways such as programmed cell death protein 1 (PD-1), its ligand PD-L1, and cytotoxic T-lymphocyte-associated antigen 4 (CTLA-4). By blocking these inhibitory signals, checkpoint inhibitors reinvigorate exhausted T cells and promote sustained immune-mediated tumor destruction. Significant

clinical successes have been observed in melanoma, non-small cell lung cancer, renal cell carcinoma, and several other solid tumors, often with long-lasting responses not typically seen with conventional therapies.

Beyond checkpoint blockade, other immunotherapy approaches are expanding the therapeutic landscape. Cancer vaccines aim to stimulate tumor-specific immune responses, while adoptive cell therapies—such as tumor-infiltrating lymphocytes (TILs) and genetically engineered T cells—offer highly personalized treatment options. Additionally, oncolytic viruses selectively infect and lyse tumor cells while simultaneously activating systemic anti-tumor immunity, further broadening the scope of immune-based interventions.

Despite its promise, immunotherapy presents unique challenges, including variable patient response rates, immune-related adverse events, and the lack of robust predictive biomarkers. Tumor microenvironment factors, immune evasion mechanisms, and tumor heterogeneity significantly influence treatment outcomes. Ongoing research into combination regimens, biomarker development, and novel immune targets is essential to optimize immunotherapy and integrate it more effectively into precision oncology frameworks for solid tumor management.

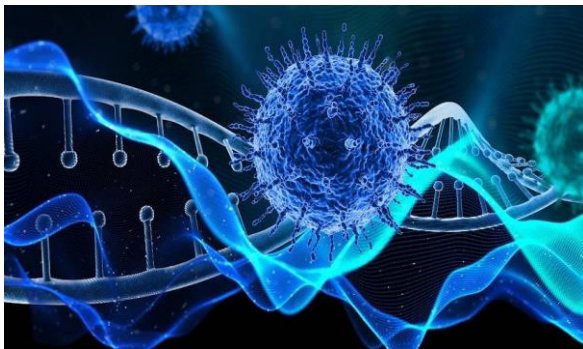


Figure 3: Immunotherapy in cancer

Combination Therapies

Combination therapies have become an increasingly important strategy in the management of solid tumors, aiming to enhance treatment efficacy by simultaneously targeting multiple oncogenic pathways or complementary biological mechanisms. Given the complexity of cancer biology and the presence of tumor heterogeneity,

single-agent treatments often lead to incomplete responses or the rapid development of resistance. By integrating different therapeutic modalities, combination approaches seek to achieve more durable tumor control and improved patient outcomes.

In precision oncology, combinations frequently involve targeted therapies paired with chemotherapy, immunotherapy, or other targeted agents. For example, combining tyrosine kinase inhibitors with immune checkpoint inhibitors can improve immune recognition while directly suppressing tumor growth signals. Similarly, dual-targeted regimens that inhibit parallel or downstream signaling pathways help prevent compensatory mechanisms that tumors use to bypass single-pathway blockade. These rationally designed combinations are increasingly guided by molecular profiling and biomarker analysis.

Combination therapies also play a critical role in overcoming therapeutic resistance. Tumors that initially respond to treatment often evolve through secondary mutations or adaptive signaling changes. By addressing multiple resistance pathways at once, combination regimens can delay or prevent disease progression. Additionally, combining systemic therapies with radiotherapy or surgery may enhance local control while reducing the likelihood of metastatic spread.

However, the use of combination therapies introduces challenges related to increased toxicity, complex dosing schedules, and higher treatment costs. Careful patient selection, optimization of treatment sequences, and ongoing monitoring are essential to balance efficacy with safety. As clinical trials continue to refine combination strategies and identify predictive biomarkers, combination therapies are expected to remain a central pillar of precision oncology, offering a more comprehensive and adaptive approach to solid tumor treatment.



Figure 4: Combination therapies machine

Intratumoral Heterogeneity and Resistance:

Intratumoral heterogeneity refers to the existence of genetically and phenotypically diverse cancer cell populations within a single tumor, arising from ongoing mutations and selective pressures during tumor evolution. This diversity enables certain subclones to survive therapeutic interventions, leading to the development of drug resistance and disease relapse. Even when a treatment effectively targets dominant tumor cells, resistant clones can expand over time, limiting long-term efficacy. As a result, intratumoral heterogeneity poses a major challenge to precision oncology, emphasizing the need for combination therapies, adaptive treatment strategies, and continuous molecular monitoring to overcome resistance and improve sustained clinical outcomes.

Access to Precision Medicine

Despite its promise, precision oncology is often inaccessible due to high costs, particularly in resource-limited settings. The cost of molecular profiling and targeted therapies can be prohibitive, especially for patients in low- and middle-income countries. Ensuring equitable access to these therapies is critical for realizing the global potential of precision oncology. In addition to financial constraints, limited diagnostic infrastructure remains a major barrier to the widespread adoption of precision oncology. Advanced molecular testing, including next-generation sequencing and companion diagnostics, requires specialized laboratory facilities, trained personnel, and bioinformatics support. In many low- and middle-income countries (LMICs), such resources are restricted to a small number of urban tertiary care centers, resulting in unequal access for patients from rural and underserved regions.

Disparities in healthcare policy, reimbursement frameworks, and regulatory approval processes compound these challenges, often delaying the availability of novel targeted therapies in resource-constrained settings. Lack of awareness among healthcare providers and patients about precision oncology options also contributes to underutilization, even where limited resources exist. Strengthening health systems through capacity building, public-private partnerships, and international collaboration is essential to bridge these gaps. Initiatives such as cost-effective genomic testing platforms, tele-oncology, shared molecular tumor boards, and inclusion of

precision diagnostics in national cancer control programs can help expand access. Addressing these structural and systemic barriers is crucial to ensuring that the benefits of precision oncology are not confined to high-income settings but are equitably distributed across diverse global populations.

Data Integration and Analysis

Data integration and analysis are central to the successful implementation of precision oncology, as they enable the meaningful interpretation of complex, multi-dimensional datasets generated from modern cancer diagnostics. Precision oncology relies on the convergence of genomic, transcriptomic, proteomic, imaging, and clinical data to create a comprehensive molecular profile of each tumor. Integrating these diverse data sources allows clinicians and researchers to identify actionable biomarkers, understand disease mechanisms, and tailor treatment strategies more accurately to individual patients.

Advanced bioinformatics platforms and analytical tools are essential for managing and interpreting the vast volumes of data produced by next-generation sequencing and high-throughput technologies. Machine learning and artificial intelligence (AI) approaches are increasingly being applied to detect patterns, predict treatment response, and stratify patients based on risk and therapeutic benefit. These computational methods enhance decision-making by transforming raw data into clinically relevant insights, supporting more precise and timely interventions.

Despite its importance, data integration faces significant challenges, including data standardization, interoperability between healthcare systems, and ensuring data quality and security. Variability in data formats, incomplete clinical records, and limited access to skilled bioinformatics personnel can hinder effective analysis, particularly in resource-limited settings. Addressing these challenges through standardized data frameworks, secure data-sharing platforms, and multidisciplinary collaboration is critical for maximizing the impact of data-driven precision oncology and improving outcomes in solid tumor management.

Artificial Intelligence and Big Data

Artificial intelligence (AI) and big data are increasingly shaping the future of precision oncology by enabling the analysis of complex, high-volume datasets that exceed

the capacity of traditional analytical methods. Modern cancer care generates vast amounts of data from genomic sequencing, medical imaging, electronic health records, pathology reports, and real-world clinical outcomes. AI-driven algorithms can integrate and analyze these heterogeneous data sources to uncover hidden patterns, identify novel biomarkers, and support more accurate diagnosis and prognosis of solid tumors.

Machine learning and deep learning techniques have shown particular promise in oncology applications such as radiomics, digital pathology, and treatment response prediction. AI models can analyze imaging data to detect subtle tumor characteristics, predict molecular alterations non-invasively, and assess therapeutic efficacy earlier than conventional methods. Similarly, in genomics, AI tools enhance variant interpretation, prioritize clinically actionable mutations, and assist in matching patients to targeted therapies or clinical trials, thereby improving the efficiency of precision medicine workflows.

Despite these advancements, the clinical integration of AI and big data faces challenges related to data quality, algorithm transparency, and ethical considerations. Biases in training datasets, lack of standardized validation, and concerns regarding patient privacy and data security can limit trust and adoption. To fully realize the potential of AI in precision oncology, robust regulatory frameworks, interdisciplinary collaboration, and continuous model validation are essential. When responsibly implemented, AI and big data have the potential to transform cancer care into a more predictive, personalized, and proactive discipline.

Expanding Precision Oncology to Rare Tumors: Currently, precision oncology has had the greatest impact on common cancers, such as lung, breast, and colorectal cancers. However, many rare cancers lack specific molecular targets and effective therapies.

Global Collaboration and Accessibility

The future of precision oncology depends on global collaboration between research institutions, pharmaceutical companies, and healthcare providers. Equitable access to molecular profiling and targeted therapies must be prioritized to ensure that all patients, regardless of socioeconomic status, can benefit from these advancements. International collaboration enables the sharing of genomic data, clinical expertise, and technological resources, which

is essential for accelerating innovation and improving treatment outcomes across diverse populations. Multinational clinical trials and global cancer genomics initiatives can help address population-specific variations in tumor biology while promoting inclusive evidence generation. Additionally, coordinated efforts to harmonize regulatory frameworks, reduce costs, and strengthen healthcare infrastructure are crucial for minimizing disparities and ensuring the sustainable and ethical expansion of precision oncology worldwide.

Conclusion

Precision oncology is poised to revolutionize cancer treatment by offering personalized therapies tailored to the unique genetic profiles of individual tumors. While significant progress has been made in the development of targeted therapies and diagnostic tools, several challenges remain, including tumor heterogeneity, therapeutic resistance, and global access disparities. Continued research, technological advancements, and collaborative efforts will be crucial in overcoming these obstacles and realizing the full potential of precision oncology. As the field continues to evolve, it holds the promise of transforming cancer care and improving outcomes for patients worldwide. Moreover, the successful integration of precision oncology into routine clinical practice will depend on the development of robust infrastructure, standardized guidelines, and interdisciplinary collaboration among oncologists, geneticists, pathologists, bioinformaticians, and data scientists. Education and training of healthcare professionals are equally important to ensure accurate interpretation of molecular data and informed clinical decision-making. Strengthening translational research and fostering seamless interaction between laboratory discoveries and bedside applications will further accelerate innovation in this field.

In addition, ethical, economic, and policy considerations must be addressed to support the sustainable growth of precision oncology. Ensuring data privacy, informed consent, and equitable access to advanced diagnostics and therapies are essential for maintaining patient trust and social responsibility. Strategic investments in health systems, particularly in low- and middle-income countries, can help bridge existing gaps and promote inclusive cancer care. Precision oncology enables personalized, biology-driven cancer care that improves outcomes and quality of life. Global collaboration and innovation are key to realizing its full impact.

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