

Precision medicine in cancer treatment: Are we there yet?

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ABSTRACT

Precision medicine (PM) is revolutionizing cancer treatment by tailoring therapies based on individual genetic, molecular, and environmental factors. This approach moves beyond traditional one-size-fits-all treatments, offering more targeted and personalized care. Advances in genomic technologies, molecular profiling, and biomarkers have led to significant progress, enabling the development of therapies, such as imatinib for chronic myeloid leukemia and BRCA-targeted treatments for breast cancer. Despite these achievements, challenges remain, including tumor heterogeneity, drug resistance, cost, and limited access to genomic testing. Ethical considerations and regulatory hurdles also impede the widespread adoption of PM. This review explores the current state of precision oncology, highlights key developments, and examines the barriers to its integration into clinical practice. It also looks toward future prospects, including the role of artificial intelligence, gene editing technologies, such as CRISPR, and liquid biopsies, all of which promise to enhance treatment personalization and improve outcomes. Continued research, policy reforms, and equitable access to advanced diagnostics and treatments are essential for unlocking the full potential of PM in cancer care.

Keywords: Biomarkers, cancer treatment, drug resistance, genomic technologies, personalized oncology, precision medicine, targeted therapies, tumor heterogeneity

Introduction

Overview of precision medicine in cancer

Precision medicine (PM) in oncology is a transformative approach that tailor's medical treatment to the individual characteristics of each patient and their disease. This method goes beyond traditional cancer treatments, which often apply a one-size-fits-all strategy, primarily relying on chemotherapy and radiation. PM utilizes genetic, environmental, and lifestyle factors to inform treatment decisions, aiming to enhance efficacy and minimize adverse effects. The significance of PM lies in its ability to address the heterogeneity of cancer; tumors can vary significantly in their genetic makeup and response to therapies, necessitating a more personalized approach to treatment.^[1]

The evolution of cancer treatment has witnessed a shift from broad-spectrum therapies to more targeted interventions. The advent of genomic sequencing technologies has enabled clinicians to identify specific mutations and molecular characteristics within tumors. This has facilitated the development of targeted therapies that can directly attack cancer cells while sparing healthy tissue, thereby improving patient outcomes.^[2]

Aim of the review

This review aims to explore the progress made in PM for cancer treatment, identify current challenges, and discuss future prospects. It seeks to address the question: "Are we there yet?" by evaluating how far PM has come in integrating into standard cancer care practices.^[3]

Progress in Precision Medicine

Advances in treatment approaches

Recent advancements in PM have led to significant improvements in cancer care. For instance, targeted therapies such as imatinib for

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chronic myeloid leukemia (CML) exemplify how identifying specific genetic mutations can lead to more effective treatments. Imatinib targets the BCR-ABL fusion protein, resulting in improved survival rates compared to traditional chemotherapy. Similarly, therapies targeting mutations, such as BRCA1/2 in breast cancer and BRAF V600E in melanoma have further demonstrated the potential of PM.^[4]

Moreover, the use of biomarkers for diagnosis and treatment monitoring has become increasingly common. Techniques such as next-generation sequencing (NGS) allow for comprehensive profiling of tumors, enabling clinicians to select appropriate therapies based on individual tumor characteristics. Liquid biopsies, which analyze circulating tumor DNA (ctDNA), have also emerged as a non-invasive method for monitoring disease progression and treatment response.

Integration into clinical practice

Despite these advancements, the integration of PM into routine clinical practice remains uneven. While some institutions have adopted PM approaches widely, others still rely heavily on traditional methods due to various barriers, including cost, access to genomic testing, and the need for specialized training among healthcare providers. Furthermore, regulatory frameworks and insurance coverage for PM treatments can be inconsistent, complicating their availability for patients.

Challenges Facing Precision Medicine

Heterogeneity of cancer

The inherent heterogeneity of cancer poses a significant challenge for PM. Different patients with the same type of cancer may respond differently to the same treatment due to variations in their tumor biology and genetics. This variability necessitates ongoing research to identify reliable biomarkers that can predict treatment responses accurately.

Cost and accessibility

The high cost associated with genomic testing and targeted therapies can limit access for many patients. Insurance coverage for these advanced treatments is often inadequate or inconsistent, creating disparities in care among different populations.^[3] Moreover, the complexity of interpreting genomic data requires specialized expertise that may not be available in all healthcare settings.^[5]

Future Prospects

Expanding applications

Looking ahead, the potential applications of PM are vast. As our understanding of cancer biology continues to evolve, new biomarkers and therapeutic targets are likely to emerge. The integration of artificial intelligence (AI) and machine learning into genomic analysis may further enhance our ability to predict treatment responses and personalize therapy more effectively.

Policy and systemic changes

For PM to become a standard part of cancer care, systemic changes are necessary. This includes improving access to genomic testing, ensuring equitable insurance coverage for precision therapies, and fostering collaboration among researchers, clinicians, and policymakers. By addressing these challenges, we can move closer to realizing the full potential of PM in oncology.

Historical Context of Cancer Treatment

Traditional approaches

For many decades, the primary methods of cancer treatment were surgery, chemotherapy, and radiation therapy. These traditional approaches operated on a “one-size-fits-all” model, where treatments were applied uniformly across patients regardless of individual differences in tumor biology or patient characteristics.

Surgery is often the first line of defense against cancer, particularly for localized tumors. It involves the physical removal of cancerous tissues and surrounding areas to prevent further spread. Chemotherapy, a systemic treatment using cytotoxic drugs, aims to kill rapidly dividing cancer cells but also affects normal cells, leading to significant side effects. Radiation therapy uses high-energy rays to target and destroy cancer cells, although it can also damage healthy tissues nearby.^[6,7]

Despite their widespread use, these conventional treatments have limitations. Chemotherapy and radiation can lead to drug resistance and are often associated with severe side effects due to their lack of specificity in targeting cancer cells. This has resulted in a growing recognition that these traditional methods may not be sufficient for all patients, prompting the need for more personalized approaches to cancer treatment.^[8]

The shift to targeted therapy

The development of molecularly targeted therapies marks a significant shift in cancer treatment paradigms. These therapies are designed to specifically target genetic mutations and molecular pathways involved in the growth and survival of cancer cells, thus minimizing harm to normal cells. The initial impact of targeted therapies has been profound; they have demonstrated improved efficacy and reduced side effects compared to traditional treatments.

For example, the identification of specific mutations such as those in the anaplastic lymphoma kinase gene has led to the development of targeted drugs, such as crizotinib, which are effective in treating non-small cell lung cancers that harbor this mutation. Similarly, PARP inhibitors, such as olaparib have shown promise in treating BRCA-mutant ovarian cancers by exploiting the DNA repair deficiencies in these tumors.^[9]

The transition from traditional therapies to targeted approaches reflects a broader movement toward PM in oncology. This evolution emphasizes the importance of understanding the unique genetic makeup of each patient's cancer, paving the way for more effective

and tailored treatment strategies that hold the potential for better outcomes and improved quality of life for patients.^[2]

Foundations of Precision Medicine

Key concepts in precision medicine

PM represents a paradigm shift in cancer treatment, focusing on tailoring medical interventions to individual patient characteristics. Central to this approach are genomics, biomarkers, and molecular profiling.

Genomics involves the comprehensive analysis of an individual's genetic makeup, which can reveal specific mutations that drive cancer development. This information is crucial for identifying targeted therapies that can effectively combat the disease. Biomarkers are biological indicators, often derived from genomic data that help in diagnosing cancer, predicting treatment responses, and monitoring disease progression. Molecular profiling refers to the detailed characterization of tumors at the molecular level, including gene expression patterns and protein profiles, facilitating the selection of appropriate therapies based on the tumor's unique characteristics.^[10]

Technological advances enabling precision medicine

Recent technological advancements have significantly propelled the field of PM. NGS allows for rapid and cost-effective sequencing of entire genomes or specific regions of interest, enabling comprehensive genomic profiling of tumors. This technology has revolutionized our understanding of cancer biology and treatment options.

Liquid biopsy is another innovative technique that analyzes ctDNA in a patient's blood sample. This non-invasive method provides valuable insights into tumor dynamics and treatment efficacy without the need for invasive tissue biopsies.^[11]

Furthermore, AI is increasingly being integrated into diagnostics and treatment planning. AI algorithms can analyze vast amounts of genomic data to identify patterns and predict patient responses to therapies, thus enhancing the precision of treatment decisions.

Role of big data in personalized oncology

The integration of big data plays a pivotal role in personalized oncology. By harnessing vast clinical and molecular datasets, researchers can identify correlations between genetic mutations and treatment outcomes across diverse populations. This data-driven approach enables clinicians to tailor treatments more effectively based on individual patient profiles.

Big data analytics also facilitates the identification of novel biomarkers and therapeutic targets, further advancing the field of PM. As more data becomes available from clinical trials and real-world evidence, the potential for refining treatment strategies and improving patient outcomes continues to grow.^[12]

Current Applications of Precision Medicine in Cancer

Targeted therapies

PM has led to the development of several successful targeted therapies. Notable examples include:

- Herceptin (trastuzumab): Used for HER2-positive breast cancer, this monoclonal antibody targets the HER2 protein overexpressed in some breast cancers
- Gleevec (imatinib): Initially developed for CML, it specifically inhibits the BCR-ABL fusion protein responsible for tumor growth in this cancer type.

Molecular profiling is critical in selecting patients for these targeted therapies. By analyzing tumor samples for specific genetic alterations, clinicians can determine which patients are likely to benefit from particular treatments, thereby optimizing therapeutic outcomes.^[13]

Immunotherapy and precision approaches

Immunotherapy has emerged as a cornerstone of PM in oncology. Treatments, such as checkpoint inhibitors (e.g., pembrolizumab and nivolumab) enhance the immune system's ability to recognize and attack cancer cells. The customization of immunotherapy based on individual patient characteristics – such as tumor mutational burden – allows for more effective interventions tailored to each patient's unique tumor environment.

Personalized cancer vaccines

Recent developments in neoantigen-based cancer vaccines represent a promising frontier in PM. These vaccines are designed to stimulate an immune response specifically against neoantigens – unique proteins expressed by an individual's tumor cells due to mutations. By personalizing vaccines to target these unique markers, researchers aim to enhance the efficacy of immunotherapy and improve patient survival rates.

Precision medicine in early detection and prevention

Advances in PM extend beyond treatment; they also play a crucial role in early detection and prevention strategies. Utilizing biomarkers for screening can identify individuals at high risk for certain cancers, allowing for earlier intervention. Personalized screening protocols based on genetic risk factors enable healthcare providers to monitor patients more closely, potentially leading to earlier diagnoses and improved outcomes.^[10]

Current Challenges and Limitations

Tumor heterogeneity

Intra-tumor genetic diversity presents a significant challenge in the field of PM. Tumors are not homogeneous; they often consist of a mixture of cells with different genetic mutations and characteristics.

This tumor heterogeneity complicates treatment strategies, as different subpopulations within a tumor may respond differently to therapies. For instance, some cells may be sensitive to targeted treatments while others may harbor mutations that confer resistance, leading to treatment failure and disease progression.^[14]

Understanding and addressing this diversity is crucial for the development of effective precision therapies.

Drug resistance

Drug resistance is a major obstacle in the effectiveness of targeted therapies. Mechanisms of resistance can be categorized into primary resistance, where tumors do not respond to treatment from the outset, and secondary resistance, which develops after an initial response. Common mechanisms include reactivation of the target pathway, activation of alternative signaling pathways, and phenotypic plasticity that allows cancer cells to adapt to therapeutic pressures.^[2,4,5] PM aims to address these challenges through combination therapies and continuous monitoring of tumor evolution; however, many current strategies still fall short in effectively overcoming resistance mechanisms.

Accessibility and cost

Economic barriers significantly limit access to PM. The high costs associated with genomic testing and targeted therapies create disparities in healthcare access. Patients in lower socioeconomic brackets or those without adequate insurance may not receive the necessary diagnostic tests or treatments, exacerbating existing health inequalities. Addressing these economic barriers is vital for ensuring equitable access to advanced cancer care.

Ethical and regulatory considerations

The rapid advancements in genomic technologies raise several ethical concerns, particularly regarding data sharing and patient privacy. The collection and analysis of genetic data necessitate stringent regulations to protect patient information while promoting research and innovation. Balancing these interests poses a significant challenge for policymakers and healthcare providers as they navigate the complexities of genomic medicine.^[15]

Limited biomarker availability

The identification of reliable, actionable biomarkers remains a significant hurdle in PM. While some biomarkers have been successfully integrated into clinical practice, many cancers lack validated biomarkers that can guide treatment decisions effectively. The variability in biomarker expression across different tumors complicates the development of universal screening protocols, limiting the applicability of precision therapies.

Recent Advances and Breakthroughs

CRISPR and gene editing in cancer treatment

Gene editing technologies such as CRISPR hold great promise for developing new precision treatments in cancer therapy. By allowing

precise modifications to the genome, CRISPR can potentially correct mutations responsible for cancer progression or enhance the sensitivity of tumor cells to existing therapies. This innovative approach could lead to personalized treatments tailored to the genetic profile of individual tumors.

Artificial intelligence and machine learning in precision oncology

AI and machine learning are increasingly being utilized in precision oncology to analyze complex datasets generated from genomic studies. These technologies can identify patterns that may not be immediately apparent through traditional analysis methods, aiding in treatment personalization by predicting patient responses based on their unique genetic makeup.^[16]

Liquid biopsies

Emerging technologies such as liquid biopsies offer non-invasive methods for cancer monitoring and treatment adjustment. By analyzing ctDNA from blood samples, clinicians can gain insights into tumor dynamics over time, enabling timely modifications to treatment strategies based on real-time data about tumor evolution and resistance mechanisms.^[17]

Future Directions

Emerging technologies

Advancements in single-cell sequencing, proteomics, and epigenomics are paving the way for more comprehensive approaches to understanding cancer biology. These technologies allow researchers to investigate tumors at unprecedented resolutions, uncovering insights that can inform more effective precision treatment strategies.

Integration of multi-omics approaches

Combining genomics, transcriptomics, and proteomics into a unified multi-omics approach promises to enhance precision treatment strategies significantly. This integrative method allows for a more holistic understanding of tumor biology, facilitating the identification of novel therapeutic targets and improving patient stratification for specific treatments.^[18]

Moving toward preventive precision medicine

The future of PM may shift from a treatment-focused paradigm to one emphasizing prevention. By leveraging genetic information and risk factors, healthcare providers could implement personalized screening protocols aimed at early detection and intervention before cancer develops or progresses significantly.

Personalized combination therapies

Developing personalized combination therapies that integrate multiple targeted agents or immunotherapies tailored to an individual's unique cancer profile is a promising direction for future research. Such strategies aim to enhance therapeutic efficacy while mitigating

resistance by simultaneously targeting different pathways involved in tumor growth.^[19]

Conclusion

Significant progress has been made in PM for cancer treatment, particularly in genomic technologies, targeted therapies, and personalized care. However, challenges, such as tumor heterogeneity, drug resistance, accessibility, and ethical issues persist, limiting its widespread adoption.

The question “Are we there yet?” highlights both advancements and the need for continued research, policy reform, and education. Overcoming these barriers is essential to fully integrate PM into oncology and improve patient outcomes.

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