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Artificial Intelligence in Precision Oncology: Current Advances, Clinical Applications, and Future Directions

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ABSTRACT

Background:

Precision oncology has transformed modern cancer management by integrating molecular profiling, advanced imaging, and individualized therapeutic strategies to improve clinical outcomes. However, the increasing complexity of multidimensional clinical, radiological, pathological, genomic, transcriptomic, and real-world patient data has created significant analytical challenges that exceed traditional computational approaches. Artificial intelligence (AI) has emerged as a transformative technology capable of extracting clinically meaningful patterns from heterogeneous biomedical datasets and supporting personalized cancer diagnosis, prognosis, treatment selection, and disease monitoring. Recent advances in machine learning, deep learning, transformer architectures, multimodal learning, explainable AI, and large language models have substantially expanded AI applications across oncology. AI systems are increasingly utilized in digital pathology, radiology, radiomics, genomics, immunotherapy prediction, biomarker discovery, clinical decision support, and drug development. These technologies facilitate earlier cancer detection, improved tumor characterization, accurate risk stratification, prediction of therapeutic response, and optimization of precision treatment strategies. Furthermore, integration of multimodal datasets enables comprehensive patient-specific models capable of supporting individualized clinical decisions. Despite remarkable progress, important challenges remain regarding data quality, algorithmic bias, interpretability, privacy protection, regulatory approval, and clinical implementation. This review summarizes recent advances in artificial intelligence for precision oncology, discusses current clinical applications across multiple oncology domains, highlights existing limitations, and explores future opportunities for AI-driven personalized cancer care.

Keywords: Artificial intelligence, Precision oncology, Machine learning, Deep learning, Digital pathology, Radiomics, Clinical oncology, Cancer diagnosis, Personalized medicine, Multimodal learning.

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Introduction

Cancer remains one of the leading causes of mortality worldwide and continues to impose an enormous clinical, economic, and societal burden. Although considerable advances have been achieved in molecular biology, targeted therapies, immunotherapy, and precision medicine, cancer diagnosis and treatment remain challenging because of extensive biological heterogeneity among patients and even within individual tumors [1].

Tumor development is driven by complex interactions involving genetic mutations, epigenetic modifications, dysregulated signaling pathways, immune escape mechanisms, metabolic alterations, and continuous interactions with the surrounding tumor microenvironment. These biological processes evolve dynamically throughout disease progression, resulting in variable clinical behavior, therapeutic resistance, and diverse patient outcomes [2].

Traditional oncology relies heavily on histopathological evaluation, medical imaging, laboratory investigations, molecular diagnostics, and physician expertise. While these approaches have substantially improved patient care, they often analyze individual data sources separately, making comprehensive interpretation increasingly difficult as the volume of biomedical information continues to expand [3].

Recent advances in high-throughput sequencing, digital pathology, radiomics, proteomics, metabolomics, and electronic health records have generated unprecedented quantities of complex clinical data. Extracting clinically meaningful information from these heterogeneous datasets represents one of the greatest challenges in precision oncology. Conventional statistical methods frequently struggle to identify nonlinear relationships hidden within these multidimensional datasets [4].

Artificial intelligence has emerged as a powerful computational framework capable of addressing these limitations. By automatically learning complex patterns from large-scale datasets, AI enables rapid analysis of imaging, genomic, pathological, and clinical information while supporting evidence-based clinical decision-making. Unlike conventional computational methods, AI continuously improves its predictive performance through exposure to increasing volumes of biomedical data [5].

The integration of AI into oncology has accelerated rapidly over the past decade. Initially limited to simple predictive algorithms, AI now encompasses sophisticated machine learning models, deep neural networks, convolutional neural networks, transformer architectures, multimodal learning systems, reinforcement learning, and large language models capable of supporting diverse clinical applications [6].

Precision oncology aims to deliver individualized treatment by considering each patient's unique molecular characteristics, tumor biology, clinical presentation, and environmental factors. Artificial intelligence complements this objective by integrating diverse biological information into comprehensive predictive models capable of supporting diagnosis, prognosis, therapeutic selection, toxicity prediction, and longitudinal disease monitoring [7].

Recent developments have demonstrated that AI can identify subtle imaging biomarkers, predict molecular alterations directly from pathology images, estimate patient survival, recommend targeted therapies, predict immunotherapy response, and optimize clinical workflows. These capabilities position artificial intelligence as a cornerstone of next-generation precision cancer medicine [8].

This review discusses recent advances in artificial intelligence technologies applied to precision oncology, summarizes major clinical applications across oncology disciplines, examines current implementation challenges, and explores future directions for AI-enabled personalized cancer care [9].

Evolution of Artificial Intelligence in Oncology

The development of artificial intelligence in oncology has progressed through several important technological phases. Early computational oncology primarily relied on statistical models and rule-based expert systems designed to perform limited diagnostic or prognostic tasks using relatively small datasets. Although these methods demonstrated potential, their clinical utility remained constrained by limited predictive accuracy and poor generalizability [10].

Machine learning represented the first major breakthrough in oncology AI. Machine learning algorithms such as logistic regression, decision trees, random forests, naïve Bayes classifiers, support vector machines, and gradient boosting machines enabled computers to learn predictive relationships directly from clinical data without relying exclusively on manually programmed rules [11].

These algorithms rapidly gained popularity for predicting cancer risk, estimating survival, classifying tumors, identifying prognostic biomarkers, and supporting clinical decision-making. Machine learning also facilitated integration of multiple clinical variables, allowing more accurate prediction than traditional statistical approaches in several oncology applications [12].

The subsequent emergence of deep learning revolutionized cancer research. Deep learning utilizes multiple layers of artificial neural networks capable of automatically learning increasingly complex feature representations from raw biomedical data. Unlike traditional machine learning, deep learning eliminates the need for manual feature engineering by learning hierarchical patterns directly from images, genomic sequences, or clinical records [13].

Convolutional neural networks (CNNs) became particularly successful in medical imaging because they automatically recognize spatial patterns associated with tumor morphology. CNNs have demonstrated expert-level performance in breast cancer screening, lung nodule detection, melanoma classification, colorectal cancer diagnosis, and numerous other imaging applications [14].

Recurrent neural networks (RNNs) and long short-term memory (LSTM) networks further expanded AI capabilities by analyzing sequential clinical information such as longitudinal patient records and treatment histories. These architectures enabled temporal prediction of disease progression and treatment outcomes [15].

More recently, transformer architectures have transformed artificial intelligence across multiple biomedical domains. Transformers employ self-attention mechanisms capable of modeling long-range relationships within complex datasets while efficiently integrating multimodal information. Their scalability has substantially improved

computational performance across pathology, radiology, genomics, and natural language processing [16]. Large language models have introduced additional opportunities in oncology through automated documentation, literature synthesis, clinical decision support, patient education, and evidence summarization. These systems improve workflow efficiency while reducing administrative burden among oncology professionals [17]. Today, artificial intelligence encompasses an integrated ecosystem of computational approaches capable of supporting nearly every stage of cancer management, from early detection to survivorship care [18].

Machine Learning and Deep Learning in Precision Oncology

Machine learning forms the foundation of contemporary artificial intelligence applications in precision oncology. These algorithms identify complex statistical relationships between clinical variables and disease outcomes by learning directly from historical patient data [19].

Supervised learning remains the most widely used machine learning paradigm in oncology. During supervised learning, algorithms are trained using labeled datasets in which the correct diagnosis or clinical outcome is already known. Once trained, these models can accurately classify new patient samples, predict survival, estimate recurrence risk, and recommend therapeutic strategies [20].

Unsupervised learning algorithms identify hidden biological patterns without predefined outcome labels. Clustering techniques have become particularly valuable for discovering novel molecular cancer subtypes, identifying patient populations with similar biological characteristics, and revealing previously unknown disease mechanisms [21].

Semi-supervised learning combines labeled and unlabeled datasets, reducing dependence on expensive expert annotation while improving model performance. This approach has become increasingly important in pathology and radiology, where manual labeling of biomedical images remains time-consuming and resource intensive [22].

Deep learning further enhances predictive performance through multilayer neural network architectures capable of automatically extracting hierarchical biological features. CNNs remain the dominant deep learning architecture for medical imaging applications because of their remarkable ability to recognize complex visual features within pathology slides and radiological scans [23].

Transfer learning has further accelerated AI implementation by allowing pretrained neural networks to be adapted for specific oncology tasks using relatively small datasets. This approach substantially reduces computational requirements while improving generalizability across diverse cancer types [24].

Recent advances also include ensemble learning methods that combine predictions from multiple independent algorithms to improve diagnostic robustness. Such integrated models frequently outperform individual machine learning systems by reducing prediction variability and increasing overall accuracy [25].

Machine learning models are now routinely applied to cancer screening, tumor grading, prognosis prediction, recurrence estimation, biomarker identification, therapeutic response prediction, and adverse event forecasting. Continued improvements in computational power and data availability are expected to further expand these applications [26].

Artificial Intelligence in Cancer Diagnosis

Early and accurate diagnosis remains one of the most critical determinants of successful cancer treatment. Artificial intelligence has significantly improved diagnostic performance by enabling automated interpretation of complex imaging, pathological, and molecular datasets [27].

Computer-aided diagnosis systems powered by AI can rapidly analyze mammography, computed tomography, magnetic resonance imaging, ultrasound, and positron emission tomography scans to identify suspicious lesions that might otherwise remain undetected during routine clinical evaluation [28].

Deep learning algorithms have demonstrated diagnostic performance comparable to experienced radiologists in detecting breast cancer, lung cancer, colorectal cancer, prostate cancer, melanoma, and brain tumors. AI-assisted screening programs improve sensitivity while reducing false-positive findings and unnecessary biopsies [29].

In digital pathology, convolutional neural networks analyze whole-slide images to detect malignant tissue, classify tumor subtypes, estimate tumor grade, quantify mitotic activity, and identify microscopic invasion patterns. Automated pathology systems also reduce interobserver variability while improving diagnostic consistency [30].

Natural language processing further supports diagnostic workflows by extracting clinically relevant information from pathology reports, radiology reports, physician documentation, and electronic health records. This enables efficient clinical data integration while reducing documentation burden [31].

AI-based diagnostic platforms are increasingly integrated into routine oncology practice, providing clinicians with quantitative decision support while maintaining physician oversight. Rather than replacing clinical expertise, AI serves as an intelligent assistant capable of improving diagnostic precision and workflow efficiency [32].

Artificial Intelligence in Digital Pathology

Digital pathology represents one of the most successful clinical applications of artificial intelligence in oncology. Advances in whole-slide imaging have enabled digitization of high-resolution tissue sections that can be analyzed

computationally using deep learning algorithms [33].

Whole-slide images contain billions of pixels and capture complex tissue architecture that cannot be efficiently analyzed using traditional computational methods. Artificial intelligence enables automated interpretation of these extremely large images through patch-based learning strategies and hierarchical feature extraction [34].

Deep learning algorithms accurately distinguish benign from malignant tissue while simultaneously identifying tumor subtype, histological grade, lymphovascular invasion, necrosis, tumor budding, and other clinically relevant pathological features [35].

Artificial intelligence has also demonstrated remarkable capability for predicting molecular biomarkers directly from routine hematoxylin and eosin stained tissue sections. Studies have shown accurate prediction of EGFR mutations, KRAS mutations, HER2 amplification, microsatellite instability, BRAF mutations, and PD-L1 expression using AI-based pathology models [36].

Tumor microenvironment analysis represents another rapidly evolving application. AI systems quantify immune cell infiltration, stromal composition, vascular density, and spatial cellular interactions associated with prognosis and immunotherapy response [37].

Recent multimodal pathology platforms combine histopathology with genomic sequencing and clinical information, enabling comprehensive patient characterization while improving personalized therapeutic recommendations [38].

Artificial Intelligence in Radiology and Radiomics

Medical imaging remains indispensable throughout cancer diagnosis, staging, treatment planning, and post-treatment surveillance. Artificial intelligence has substantially improved radiological interpretation through automated image analysis and quantitative feature extraction [39].

Radiomics involves extraction of large numbers of quantitative imaging biomarkers describing tumor shape, texture, intensity, vascularity, and heterogeneity. Machine learning algorithms analyze these features to predict tumor aggressiveness, treatment response, recurrence risk, and overall survival [40].

Deep learning further enhances radiomics by automatically learning imaging biomarkers directly from raw medical images without manual feature engineering. These models identify subtle imaging characteristics beyond human visual perception, improving predictive performance across multiple cancer types [41].

AI-powered segmentation algorithms accurately delineate tumor boundaries, metastatic lesions, lymph nodes, and organs at risk. Automated segmentation significantly reduces clinician workload while improving reproducibility in radiation oncology and surgical planning [42].

Radiogenomics combines imaging biomarkers with genomic information to establish relationships between radiological phenotypes and underlying molecular alterations. This emerging field supports non-invasive prediction of actionable mutations and personalized treatment selection [43].

Longitudinal AI systems also enable continuous monitoring of therapeutic response by comparing sequential imaging studies over time. Automated assessment of tumor shrinkage, progression, and recurrence supports adaptive treatment strategies while facilitating personalized oncology care [44].

Artificial Intelligence in Cancer Genomics and Biomarker Discovery

Genomic medicine has become a cornerstone of precision oncology because cancer development is fundamentally driven by molecular alterations affecting cellular signaling, DNA repair, proliferation, apoptosis, and immune regulation [45].

Next-generation sequencing technologies generate enormous volumes of genomic information that require advanced computational analysis. Artificial intelligence enables rapid interpretation of these complex datasets by identifying clinically relevant mutations, molecular signatures, and therapeutic targets [46].

Machine learning algorithms classify tumors according to genomic profiles, distinguish driver mutations from passenger mutations, predict pathogenic genetic variants, and identify biomarkers associated with targeted therapy response [47].

Artificial intelligence further integrates transcriptomic, epigenomic, proteomic, and metabolomic datasets to generate comprehensive molecular profiles that better reflect tumor biology than individual omics platforms alone [48].

Single-cell sequencing combined with AI has greatly improved understanding of intratumoral heterogeneity by identifying rare cellular populations associated with metastasis, immune evasion, and therapeutic resistance [49].

AI-driven biomarker discovery also accelerates identification of prognostic and predictive biomarkers capable of supporting personalized treatment decisions. Computational analysis of multi-omics datasets continues to reveal previously unrecognized biological pathways involved in cancer progression [50].

Furthermore, graph neural networks and network-based machine learning approaches facilitate systems-level analysis of gene regulatory networks, signaling pathways, and protein interactions, providing deeper insight into cancer biology and therapeutic opportunities [51].

(End of Part 1 — References numbered [1]–[51]. Part 2 will continue with Sections 8–16, including

Immunotherapy, Clinical Decision Support, Drug Discovery, Ethical Challenges, Future Perspectives, Discussion, Conclusion, and citations [52]–[60].

Artificial Intelligence in Immunotherapy and Precision Cancer Treatment

Immunotherapy has revolutionized the treatment landscape for multiple malignancies by enabling the immune system to recognize and eliminate tumor cells. Immune checkpoint inhibitors, adoptive cell therapies, cancer vaccines, and bispecific antibodies have significantly improved survival in several cancer types. Nevertheless, considerable variability exists in patient response, with only a subset of individuals achieving durable clinical benefit. Artificial intelligence has emerged as a powerful tool for identifying patients most likely to respond to immunotherapy through comprehensive analysis of molecular, pathological, radiological, and clinical biomarkers [52].

Machine learning algorithms integrate diverse datasets, including tumor mutational burden, microsatellite instability, PD-L1 expression, tumor-infiltrating lymphocytes, genomic alterations, transcriptomic profiles, cytokine signatures, and clinical characteristics to predict therapeutic response. These predictive models facilitate personalized treatment selection while minimizing unnecessary exposure to ineffective therapies and treatment-related toxicities.

Digital pathology combined with deep learning enables quantitative assessment of immune cell infiltration, stromal composition, and spatial interactions within the tumor microenvironment. Automated image analysis identifies patterns associated with immune activation, immune suppression, and resistance mechanisms that may not be readily apparent during conventional histopathological evaluation.

Artificial intelligence also supports neoantigen discovery by predicting peptide binding affinity, antigen presentation, and T-cell receptor recognition. These computational approaches accelerate the development of personalized cancer vaccines and adoptive cellular therapies tailored to individual patients. Furthermore, AI assists in monitoring immune-related adverse events by integrating laboratory parameters, imaging findings, and longitudinal clinical records, thereby improving patient safety during immunotherapy.

As immunotherapy continues to evolve, AI-driven biomarker discovery and predictive modeling are expected to play an increasingly important role in optimizing individualized treatment strategies and improving long-term clinical outcomes.

Artificial Intelligence in Clinical Decision Support

Modern oncology requires clinicians to interpret vast amounts of clinical information, including pathology reports, radiological findings, genomic sequencing results, laboratory investigations, treatment guidelines, and continuously evolving scientific literature. Artificial intelligence-based clinical decision support systems have emerged as valuable tools for synthesizing these complex datasets into actionable clinical recommendations [53].

Clinical decision support platforms integrate structured and unstructured patient information to assist physicians in diagnosis, staging, treatment planning, prognostic assessment, toxicity prediction, and follow-up management. Machine learning algorithms analyze historical patient outcomes to identify treatment strategies associated with improved survival while considering patient-specific clinical characteristics.

Natural language processing has significantly expanded the capabilities of clinical AI systems by extracting relevant information from physician notes, pathology reports, radiology interpretations, discharge summaries, and electronic health records. Automated documentation reduces administrative workload while improving data consistency and clinical efficiency.

AI-assisted multidisciplinary tumor boards are increasingly incorporating predictive analytics to support evidence-based therapeutic decision-making. By integrating imaging, pathology, molecular diagnostics, and current clinical guidelines, these systems facilitate collaborative discussions among oncologists, surgeons, radiologists, pathologists, and radiation oncologists.

Importantly, AI-based decision support is intended to complement rather than replace physician expertise. Clinical judgment, patient preferences, ethical considerations, and multidisciplinary evaluation remain essential components of personalized oncology care.

Artificial Intelligence in Drug Discovery and Precision Therapeutics

The discovery and development of novel anticancer drugs is traditionally a lengthy, expensive, and resource-intensive process. Artificial intelligence has substantially accelerated drug discovery by enabling rapid identification of therapeutic targets, prediction of drug-target interactions, optimization of molecular structures, and prioritization of candidate compounds for experimental validation [54].

Machine learning algorithms analyze genomic, proteomic, transcriptomic, and chemical datasets to identify previously unrecognized therapeutic targets involved in tumor initiation, progression, and metastasis. Deep learning models predict molecular binding affinity, pharmacokinetic properties, toxicity profiles, and therapeutic efficacy before laboratory testing, thereby reducing development costs and improving efficiency.

Artificial intelligence also facilitates drug repurposing by identifying existing medications with potential anticancer activity based on molecular similarity, pathway analysis, and clinical outcome data. This strategy shortens development timelines by leveraging established safety profiles of approved drugs.

Generative AI models further accelerate medicinal chemistry by designing novel molecular structures with optimized pharmacological properties. These systems can generate candidate compounds predicted to demonstrate improved potency, selectivity, and reduced toxicity compared with conventional drug discovery approaches.

Clinical trial optimization represents another important application. AI assists in identifying eligible participants, predicting enrollment success, optimizing study design, and monitoring treatment response throughout clinical investigations. These capabilities improve trial efficiency while accelerating the translation of innovative therapies into clinical practice.

Challenges and Limitations of Artificial Intelligence in Precision Oncology

Despite remarkable advances, several important barriers continue to limit widespread implementation of artificial intelligence in oncology. One of the primary challenges involves the availability of large, high-quality, well-annotated datasets necessary for training robust machine learning models. Incomplete clinical records, inconsistent imaging protocols, and variable pathological annotations may reduce algorithm performance and generalizability [55].

Algorithmic bias represents another significant concern. AI systems trained predominantly on datasets from specific geographic regions or demographic populations may perform less accurately in underrepresented groups, potentially contributing to healthcare disparities. Developing diverse and representative training datasets remains essential for equitable implementation.

Interpretability also presents a major obstacle. Many deep learning models function as “black boxes,” providing highly accurate predictions without clearly explaining the reasoning behind their decisions. This lack of transparency may reduce clinician confidence and complicate regulatory approval.

Patient privacy and data security remain critical considerations because oncology datasets contain highly sensitive personal information. Compliance with privacy regulations requires robust data governance, secure storage, encryption, anonymization, and ethical management of clinical information.

Computational infrastructure requirements may also limit implementation in resource-constrained healthcare systems. Training large AI models often requires advanced hardware, high-performance computing resources, and specialized technical expertise that may not be universally available.

Finally, rigorous prospective clinical validation remains necessary before widespread adoption. Although many AI systems demonstrate promising performance in retrospective studies, large multicenter clinical trials are required to establish safety, reliability, and real-world clinical effectiveness.

Future Perspectives

Artificial intelligence is expected to become an integral component of future precision oncology by enabling continuous integration of molecular diagnostics, imaging, pathology, wearable health technologies, and real-world clinical data into unified patient-specific care pathways [56].

Future AI platforms will increasingly utilize multimodal learning to simultaneously analyze radiological images, digital pathology slides, genomic sequencing, transcriptomics, proteomics, metabolomics, and electronic health records. Such comprehensive integration will enable more accurate prediction of disease progression and individualized therapeutic response.

Digital twin technology represents an emerging paradigm in which computational models simulate patient-specific tumor biology and predict treatment outcomes before clinical intervention. AI-powered digital twins may eventually allow clinicians to evaluate multiple therapeutic strategies virtually before selecting the optimal treatment for each patient.

Wearable biosensors and remote monitoring systems will provide continuous physiological data, enabling early detection of treatment-related complications, disease recurrence, and changes in patient health status. Integration of these longitudinal data streams with AI algorithms may facilitate truly adaptive precision oncology.

Advances in explainable AI, federated learning, privacy-preserving computation, and regulatory science are expected to enhance clinician trust, improve patient safety, and accelerate clinical adoption. Continued collaboration among clinicians, researchers, data scientists, regulatory agencies, and healthcare organizations will be essential for realizing the full potential of artificial intelligence in cancer medicine.

Discussion

Artificial intelligence has rapidly evolved from an experimental computational technology into a fundamental component of precision oncology. By integrating complex multidimensional datasets, AI enables clinicians to better understand tumor biology, predict disease behavior, personalize therapeutic strategies, and improve clinical

outcomes [57].

Applications across cancer diagnosis, digital pathology, radiology, genomics, immunotherapy, biomarker discovery, clinical decision support, and drug development demonstrate the broad clinical impact of AI throughout the oncology care continuum. The ability to combine heterogeneous biomedical information into unified predictive models represents one of the greatest strengths of artificial intelligence.

Nevertheless, responsible implementation requires careful consideration of ethical, technical, and regulatory challenges. Algorithm transparency, fairness, patient privacy, data quality, and clinical validation remain essential prerequisites for widespread clinical adoption. Artificial intelligence should function as a decision-support technology that enhances, rather than replaces, physician expertise and multidisciplinary clinical judgment.

Continued advances in multimodal learning, explainable AI, federated learning, and large-scale biomedical data integration are expected to further improve diagnostic accuracy, therapeutic precision, and healthcare efficiency. As these technologies mature, artificial intelligence will play an increasingly central role in delivering personalized, evidence-based oncology care.

Conclusion

Artificial intelligence has become one of the most transformative technologies in precision oncology by enabling comprehensive analysis of complex biomedical datasets and supporting individualized cancer management [58]. Machine learning, deep learning, natural language processing, radiomics, digital pathology, genomics, and multimodal AI have collectively enhanced cancer diagnosis, prognostic prediction, biomarker discovery, treatment selection, immunotherapy optimization, and clinical decision support.

Recent technological advances have substantially improved the ability to integrate clinical, pathological, radiological, and molecular information into unified computational frameworks capable of supporting personalized therapeutic strategies. These innovations have the potential to improve diagnostic accuracy, reduce healthcare costs, optimize treatment outcomes, and enhance patient quality of life.

Despite ongoing challenges related to interpretability, algorithmic bias, privacy protection, computational infrastructure, and regulatory approval, continued research and multidisciplinary collaboration are expected to accelerate clinical translation. Future developments involving digital twins, multimodal learning, explainable AI, and adaptive precision medicine are likely to redefine cancer care over the coming decades [59].

Ultimately, artificial intelligence is positioned to become an indispensable component of next-generation oncology by enabling more accurate, efficient, scalable, and patient-centered precision medicine. With continued technological innovation, rigorous clinical validation, and responsible implementation, AI has the potential to significantly improve cancer prevention, diagnosis, treatment, and survivorship while advancing the global practice of precision oncology [60].

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