International Journal of General Medicine

Dovepress
Taylor & Francis Group

Open Access Full Text Article

COMMENTARY

The New Era of Precision Oncology. Practicing Pathology in Low Resource Countries and Settings

Zubair Ahmad[1], Shabina Rahim[2], Maha Zubair[3], Jamshid Abdul-Ghafar[4]

[1]Department of Pathology, Sultan Qaboos Comprehensive Cancer Care and Research Centre, Muscat, Oman; [2]Pathology Department, Royal Medical Services, Military Hospital, Manama, Bahrain; [3]Department of Internal Medicine, LSU Health Shreveport, Shreveport, LA, USA; [4]Department of Pathology and Clinical Laboratory, French Medical Institute for Mothers and Children (FMIC), Kabul, Afghanistan

Correspondence: Jamshid Abdul-Ghafar, Department of Pathology and Clinical Laboratory, French Medical Institute for Mother and Children (FMIC), Kabul, Afghanistan, Tel +93792827287, Email jamshid.jalal@fmic.org.af

Abstract: Personalized or precision medicine is the future of cancer treatment modalities. It is advancing at a rapid pace and transforming the practice of oncology. Personalized oncology demands personalized (precision) pathology. New biomarkers are continuously being discovered, and there is increasing emphasis on individualized care. The primary aim of oncology in the new era is to utilize the molecular characteristics of malignant tumors to design the best and most optimal treatment for each cancer patient. Molecular diagnostics is the cornerstone of precision oncology. Pathology always had a crucial and major role in cancer care encompassing all aspects of oncology and this role is becoming even more critical. It is expanding and transforming into an even more dynamic specialty. Pathologists in developing countries and low resource settings need to understand these changes, take up the new challenges and opportunities, and modify their practice accordingly not only in order to remain relevant, but even more importantly to embrace a more central and vital role in cancer care. They need to embrace molecular technologies like next-generation sequencing (NGS) and familiarize themselves with new and emerging molecular biomarkers, and how these help in deciding the best targeted therapy for individual cancer patients. They also need to incorporate digital pathology (DP) and artificial intelligence (AI) in their routine practice. Herein, we present our views and perspective regarding opportunities and challenges for pathologists in the era of "precision oncology".

Keywords: precision, pathology, oncology, developing country

Introduction

Modern pathology traces its roots Virchow and the development of cellular pathology in the nineteenth century, and became more streamlined as a clinical discipline in the early twentieth century. The introduction of immunohistochemistry (IHC) in 1980 represented a crucial milestone which transformed the practice of pathology. Subsequently, critical developments occurring in the first decade of the new millennium included the development of the first institutional assays for personalized medicine in 2004 and next-generation sequencing (NGS) in 2010. Another revolution in pathology is currently underway in the form of Digital Pathology (DP) and Artificial Intelligence (AI). The first digital scanner for primary diagnosis was cleared by FDA in 2017,[1] while the development of AI-based pathology algorithms has already started to play a major role in improving cancer care.[2]

In this article, we will present our perspective regarding the opportunities and challenges for pathologists, especially those practicing in low resource settings/countries in the era of precision oncology. We hope the underlying text will help pathologists in understanding these changes and encourage them to embrace new technologies and methods, thus assuming a more central role in cancer care. We will discuss the role of molecular biomarkers and their essential role in deciding the best personalized treatment for individual cancer patients, as well as the NGS-based technologies which make this happen. We will also talk about the role of DP and AI in pathology, and discuss the difficulties and challenges

https://doi.org/10.2147/IJGM.S593156
Received: 1 January 2026
Accepted: 19 March 2026
Published: 24 March 2026

(development of infrastructure and its sustainability, and availability as well as training and retention of manpower) in low-resource settings and the ways these can be tackled.

Precision Oncology and Precision Pathology

Personalized or precision medicine is the future of cancer treatment modalities. Advances in genomics are impacting contemporary oncology practice. New molecular biomarkers are being discovered at a rapid pace and being incorporated in cancer care. The focus is now on individualized care. Currently, the primary aim of oncology is to utilize the power of molecular biomarkers to design the best treatment benefits for each cancer patient. The core of precision medicine is to optimize the best therapeutic strategy for individual patients based on the genomic and molecular profiling of their cancer[3] The role of pathologists in cancer care is becoming even more crucial and central, encompassing all aspects of oncology.

Discussion

For a long time, morphology has been considered the "gold standard" for diagnosis of cancer, but it is now increasingly recognized that morphology alone may not be sufficient to determine the clinical behavior of a cancer. Thus, tumor markers are being increasingly used as predictive tools in determining the response to targeted cancer treatments. It may become increasingly difficult to justify the old concept of the pathologist as a physician who looks through the microscope and makes a diagnosis. Whereas until recently, pathologists were mainly required to define prognostic biomarkers, they are now increasingly required to define predictive biomarkers as well.[4,5] The wide range of molecular genetic technologies now available, and continuous rapid discovery of new molecular biomarkers, are reshaping how pathologists work and beginning to have a direct impact on the practice of pathology. The correlation of molecular findings with morphology is now essential.[6,7]

Morphological examination of cancer tissue under the microscope (H&E, IHC) is still extremely important both for diagnosis and prognosis, and the role of microscopy is still expanding. Some examples of importance of microscopy in providing essential prognostic and predictive information include reporting ER, PR, HER2 and tumor infiltrating lymphocytes (TILs) in breast cancer, MMR in gastrointestinal cancers, PD-L1 and p16 in several cancers etc.

Two examples of the prognostic role of H&E are provided here.

Pathologists must report the response to chemotherapy in post-chemotherapy resection specimens.

In breast cancer, Residual cancer burden (RCB) is a pathological scoring system combining information about the tumor bed and the axillary nodes. This information is used to calculate an RCB score. RCB 0 indicates a pathological complete response (pCR), meaning no cancer is detectable RCB I, II, and III indicate increasing amounts of residual cancer. RCB score is a reliable indicator of long-term prognosis and survival. It helps clinicians determine the best course of adjuvant therapy. While pCR is a positive outcome, some of these patients still experience recurrence, and some without pCR have good long-term outcomes. RCB provides a more nuanced assessment of treatment response. It helps identify patients who need more aggressive treatment based on the extent of residual cancer. Thus, it provides valuable information about a patient' helping oncologists tailor treatment strategies and potentially improve long-term outcomes for breast cancer patients.[8–10] Pathologists can also grade the treatment response using the Miller-Payne grading system with grades 1 to 5 indicating increasingly effective tumor response. Grade 5 signifies pathological complete response (no malignant cells are seen although DCIS may be present, only stroma and macrophages are seen only). The Miller-Payne system is also useful in stratifying survival outcomes of post-chemotherapy patients.[11]

In colorectal cancer (CRC), neoadjuvant chemotherapy is associated with significant tumor response and better prognosis. The College of American Pathologists recommends modified Ryan scheme, based on the scheme proposed by Ryan et al,[12] for reporting tumor regression score from 0 to 3, with score 0 signifying complete tumor response (no viable cancer cells present, while score 3 signifies poor or no response (extensive residual cancer with no evident tumor regression).

Cold Ischemia Time in Cancer Specimens

It is worthwhile to briefly discuss the importance of cold ischemia time as an essential assurance tool in cancer specimens. Cold ischemia time represents the time duration before tissue is fixed following the biopsy/surgical procedure. The general recommendation is to keep it as short as possible. It is critical because prolonged cold ischemia time can negatively affect the quality of proteins and RNA, leading to inaccurate test results for IHC and molecular studies performed on the tissue. For breast cancer, ASCO/CAP guidelines recommend minimizing it to less than one hour to ensure reliable results. For DNA testing, it should be less than 1 hour for FISH, and 24 hours or less for PCR; it should be less than 12 hours each for RNA and protein; and less than 6 hours for morphology.[13] Labs need to clearly communicate to the OR about the importance of ensuring correct cold ischemia times and mentioning it on the requisition slips. Standardized procedures for specimen handling and transport should be developed at institutional levels. Cold ischemia time and fixation time must be clearly mentioned in pathology reports of cancer specimens. In breast cancer, where biomarkers (ER, PR, and HER2) are essential for determining cancer type and aggressiveness as well as for determining the best treatment options, minimizing cold ischemia time is critical.[14,15]

Pathologists as Collaborative Clinicians

In the currently evolving scenario, pathologists will increasingly become collaborative clinicians and definitively enter the domain of clinical management of cancer. They will be expected to predict risk of cancer development, diagnose early/precursor lesions, identify treatment targets, measure and monitor tumor mutational burden etc. They will also have a crucial role in identifying patients who will benefit from properly targeted immunotherapies. They will now work and collaborate actively with multidisciplinary teams in tumor boards including molecular tumor boards (MTBs) to help decide treatment for individual cancer patients. They will serve alongside oncology care teams. Histopathologists are a core part of MTBs because they provide the crucial histopathological context for the molecular findings.[16,17] A recent study by Volders et al recommends the establishment of national molecular tumor boards to decide the best treatment for individual cancer patients.[18]

Comprehensive Genomic Profiling (CGP)

Precision medicine is the future of treatment modalities for cancer. Until a few years back, single marker molecular testing was performed in different cancers. However, its utility is decreasing with every passing day. There is an increasing need for CGP of malignant tumors for more accurate diagnosis and prognostication and identifying potential therapeutic targets. Considerable advancements in NGS technologies have increased the use of CGP as the primary tool for deciding personalized, precise molecular-based treatment of cancer.[19] CGP is an advanced molecular diagnostic testing technology which uses NGS to analyze hundreds of genes simultaneously in a single tumor sample, and identifies actionable mutations in various cancers to help decide targeted therapies and immunotherapies in individual cancer patients based on the identified genomic alterations. It identifies all four main classes of genomic alterations-SNVs, indels, CNVs, and fusions, as well as complex molecular signatures of cancers such as tumor mutation burden (TMB), microsatellite instability (MSI) etc. It provides opportunities to understand differences in the biology of malignant tumors at the time of initial diagnosis and at tumor recurrence. CGP is critical to understanding intra-tumor heterogeneity and therapeutic resistance and developing the most effective treatment strategies. A recent study by Hung et al highlighted the crucial role of CGP in identifying actionable genomic alterations and deciding effective treatments for individual cancer patients.[20] CGP is increasingly considered the cornerstone of precision oncology.

With technologies like CGP, pathologists can determine molecular signatures of various cancers thus allowing patients to receive personalized therapies for their cancers. Pathologists will use their expertise to combine morphological and molecular information resulting in an integrated report providing definitive diagnosis as well as accurate prognostic and predictive information. Such integrated reports will allow cancer patients, including those with metastatic tumors, to receive optimum treatment. Pathologists will thus acquire a major role in helping clinicians in designing tailored treatment regimens (therapy selection), so that cancer patients receive the best personalized treatment for their cancers. Thus, the role of pathologists will become more challenging and demanding. They will need to be diagnosticians as well

as clinicians. The broadening role of pathology represents a significant challenge to pathology practices. These challenges must be addressed in training programs and the workflow in pathology departments.

A number of robust and comprehensive CGP solutions are commercially available and provide accurate and rapid results allowing patients to receive the best cancer therapy based on the precise molecular characteristics of their cancer.

Integration of Morphology and Molecular Changes for Optimal Treatment

This new era is that of "big data" and personalized medicine.[21] In this exciting time, pathologists need to understand that initiative and new innovations are required for comprehensive integration of morphology and molecular characteristics of each cancer as cancers can no longer be treated based on morphologic subtypes alone. The diagnosis and treatment of cancer will depend on the integration of molecular biomarkers and morphology. Pathologists are responsible for this integration and for interpreting the integrated findings.[22,23] For example, many different mutations are seen in adenocarcinoma of lungs, and individual patients need to be treated differently based on the presence of specific mutations (new specific treatments are becoming available) irrespective of the morphologic appearance which may be similar. Similarly, other cancers in the body also show many different mutations, and major cancer types also show a range of molecular alterations. Similar molecular changes may occur in different cancers which means the same targeted therapies can be given in all cancers manifesting the same molecular alterations. For example, HER2 overexpression is seen in breast, gastric and lung cancer, while BRAF alterations occur in melanoma, and colon cancer. Although few personalized treatment options are currently available for primary CNS neoplasms in spite of major advances in the molecular profiling and classification of these tumors, a recent study highlighted the role of molecularly guided treatment in CNS neoplasms.[24] Pathologists must communicate effectively with clinicians for optimal patient care. A new approach being advocated these days is that pathologists also meet directly with cancer patients to explain the pathology report. The reports should be so phrased that cancer patients themselves can fully understand their disease, treatment options, and participate in shared decision making. In other words, pathologists should deliver consumable pathology reports for cancer patients. Clinicians are sometimes impatient as they need to start treatment but will need to understand that effective communication with pathologists will help in the selection of the best therapy for the patients. In addition to an initial microscopic examination, pathologists can determine whether there is enough tumor tissue for additional testing and whether a liquid biopsy is feasible. To emphasize again, future pathologists will no longer be solely focused on diagnosis but will also have a crucial role in integrating molecular and morphologic information, refining cancer classification and identifying potential therapeutic targets to guide treatment decisions and predicting patient outcomes. With the continuous advances in genomic and molecular testing and the gradual transformation of pathology in embracing molecular testing, the role of the next-generation pathologists is increasingly critical in cancer care. They will play a vital role in treatment selection based on the specific molecular characteristics of a particular cancer. They will help determine which drugs will be most effective a particular patient. In addition, they will play a major role in monitoring how effective the response to a particular treatment by analyzing biopsies taken during and after treatment, and predicting relapses. Thus, pathologists will be at the forefront of translational research and will be part of clinical trials collaborating with researchers and pharmaceutical companies to develop new diagnostic tests, identifying new biomarkers and drugs.

DP and AI Solutions

The term "AI" means a field in computer science that emulates human intelligence by computers designed to think and act like humans in similar situations. In other words, AI refers to intelligent machines that think and act like humans. AI now has a vital role in medicine. Deep learning (DL) and machine learning (ML) are subtypes of AI. DL refers to machines that can think like human brain using artificial neural networks. ML refers to systems that learn things based on experience and provide defined data in order to make proper decisions.[25]

With the recent approvals of whole slide imaging (WSI) scanners for primary diagnosis by FDA, DP and AI-based pathology algorithms (digital pathology solutions) will be increasingly used by pathologists for quicker diagnosis of cancer.[26] DP has transformed the traditional pathology practice of analyzing cancer tissue microscopically into a computer vision workflow.[27] It is being increasingly adopted by the pathology community,[28] and makes it easier to

get second opinion from experts, thus enhancing collaboration and efficiency among pathologists worldwide. Integrating DP with AI and ML algorithms improves diagnostic accuracy.[29] Integration of DP with AI produces high-quality images and allows rapid definitive diagnosis, potentially leading to better cancer management. AI algorithms can identify very subtle histopathologies which may be missed by manual examination. The enhanced diagnostic accuracy and faster speed of AI is extremely important for early detection of those cancers which need to be treated quickly. The integration of AI and DP allows pathologists to identify tumor areas histologically accurately and with unprecedented speed in multiple cancers and is already being used in clinical settings in common cancers including breast and prostate. In breast cancer, for example, they help in diagnosis, grading, biomarker evaluation, and predicting response of the tumor to neoadjuvant therapy.[30,31] Similarly, AI solutions are facilitating early and rapid diagnosis of lung, gastrointestinal and skin cancers. Many of these diagnostic and predictive clinical AI solutions are FDA approved. FDA approvals for AI in pathology are accelerating rapidly. Some examples of how AI-based algorithms address key unmet needs in pathology include VENTANA DP 600 high-volume slide scanner (FDA approval received on January 9, 2025), IBEX Galen Prostate (Ibex Prostate Detect) for primary diagnosis of prostate cancer (FDA approval received in February 2025), ROCHE HER2 and ISH solutions for biomarker assessment (FDA approval received in December 2025), HER2-low/ultralow (FDA approval received in January 2025) and ROCHE IHC DP, VENTANA TROP2 for risk prediction and determining patient treatment (FDA approval received in April 2025), Path Assist Derm or PathAI (FDA approval received in March, 2026) etc.[32–35]

The promise of AI enabled morphology biomarkers lies in their ability to directly and rapidly determine cancer subtypes from digital images of H&E slides. They are based on widely available, low-cost technology. Number of molecular tests needed can potentially be reduced. In other words, AI-driven revolution in medicine is beginning to place pathologists in the center of personalized health care. They are becoming more integral to the entire spectrum of cancer care, from diagnosis to treatment and beyond. Pathologists need to take advantage of AI and computer-aided decision making in their daily practice.

Currently, there is a status quo from a clinical perspective. Although the number of AI solutions is rapidly increasing, relatively few applications are currently being used in clinical practice and there is not a significant impact on physicians and patients. There are insufficient regulatory standards and unresolved legal and billing issues. However, these issues will hopefully be resolved soon with greater integration into routine pathology practice and cancer care.

ctDNA and CTCs

ctDNA found in the blood of cancer patients as a result of death and breakdown of cancer cells. It is the portion of cell-free DNA in the blood of cancer patients released from cancer cells as a result of apoptosis, necrosis, or active release.[36] It has emerged as a useful biomarker as shown by its increasing adoption in clinical practice.[37] It can be analyzed through liquid biopsies to gain knowledge about cancer's genetic makeup. ctDNA acts as a biomarker, carrying tumor-specific genetic information and offers a minimally invasive option to diagnose cancers and to monitor the disease in individual cancer patients.[38] ctDNA analysis can help to diagnose certain cancers, especially when tissue biopsies are difficult or impossible to obtain. Changes in ctDNA levels can indicate how well a patient is responding to treatment (treatment monitoring), with decreasing levels suggesting a positive response and increasing levels potentially indicating resistance or recurrence. Its analysis can be used to detect minimal residual disease (MRD) after treatment, and its detection may potentially signal the early stages of cancer recurrence (early detection of recurrence). ctDNA analysis can help identify specific mutations in the tumor, guiding the selection of targeted therapies. A lack of ctDNA in the bloodstream in periods with no symptoms following treatment may be an indication that the cancer has not returned and is in remission. High ct DNA tumor fraction (TF) is a characteristic of high shedding metastatic and more advanced stage and aggressive cancers which are progressing while patient is under active treatment. Low ct DNA TF is a characteristic of low shedding cancers still limited to tissue of origin or locally advanced, and cancers which are shrinking and responding well to treatment. Thus, low quantity of ctDNA may indicate that treatment is successful. ctDNA TF value helps decide the next steps following a negative liquid biopsy result. It can be used to decide performing a tissue biopsy for confirmation in such patients. However, it is very important to understand that false positives or false negatives can occur. As ctDNA constitutes less than 1% of the total DNA in blood, its sensitivity is low, and detection, especially in the early stages of

cancer or when tumor burden is low, may be difficult with current technologies, giving rise to false-negative results. Conversely, false-positive results can occur indicating the presence of cancer where there is none, as white blood cells can acquire mutations under certain conditions. Sometimes, DNA shed from successfully treated or benign tumors might be detected giving rise to false-positive results. It is not a replacement for traditional tissue biopsies and is often used in conjunction with them.

CTCs are intact cancer cells rather than just DNA fragments. CTCs not only reveal that cancer is present but also provide a useful clue regarding its behavior, may represent the seeds of metastases, and help in the selection of the best therapy.

Liquid biopsies may allow the identification of genomic alterations in various cancers and the selection of the most appropriate targeted therapy for patients eligible for such therapies. Patients can receive therapy (when required) which is beneficial and changes the course of their treatment. For example, presence of PD-L1 protein on a CTC in a melanoma patient may indicate that immunotherapy may be a better option.

Thus, knowing more about cancer from a patient's blood sample (liquid biopsy) by examining ctDNA or CTCs or both in combination is an approach that is now being applied to cancers of breast, colorectum, urinary bladder, prostate, pancreas, and lung as well as malignant melanoma. The amount of ctDNA increase as the cancer grows. Preliminary data shows that ctDNA levels in liquid biopsies can help in the selection of the best therapies in various cancers as well as monitoring how effective a particular therapy. They can also provide clues about possible involvement of liver, bones etc. without invasive procedures. The technique is still evolving. Ongoing clinical trials in the next few years may reveal the true value and full potential of liquid biopsies in various cancer types and clinical settings and determine whether they can truly help in providing the best care for cancer patients. Opinion is still divided whether a "plasma first" or "tissue first" approach is better.

Surrogate IHC Markers

IHC markers can serve as surrogates in place of molecular testing, providing a practical tool for rapid, accurate, and more affordable and cost-effective cancer diagnosis. These are being increasingly used to indirectly identify genetic alterations in cancers by detecting specific proteins whose expression is linked to those alterations. Examples of surrogate IHC markers are discussed below: The SS18::SSX fusion is a genetic hallmark of SS. Specific antibodies targeting the fusion protein can be used as a surrogate to identify SS;[39] MUC4 expression is strongly associated with fusions in low-grade fibro myxoid sarcoma;[40] DDIT3 (CHOP) translocation is a key genetic event in myxoid liposarcoma. DDIT3 IHC can identify the presence of the DDIT3 fusion protein;[41] ALK and ROS1 for inflammatory myofibroblastic tumors;[42] CAMTA1 for epithelioid hemangioendothelioma;[43] NKX2.2 overexpression is a hallmark of EWSR1::FLI1 fusion in Ewing Sarcoma,[44] IDH1 (R132H) mutations are common in gliomas, and IHC staining for this specific IDH mutation can be used as a surrogate marker; p53 IHC (intense nuclear staining) can be a surrogate marker for TP53 mutations in gliomas and other cancers. ATRX, BRAF V600E, CDKN2A are also important surrogate IHC markers in gliomas.[45–49] As IHC is widely available, surrogate IHC markers are invaluable diagnostic tools for pathologists in resource-limited settings when molecular testing such as CGP is too expensive and not readily available. Surrogate IHC markers can also help determine response of a cancer whether it is likely to respond to specific targeted therapies, for example tyrosine kinase inhibitors. However, it must be emphasized that surrogate IHC markers are not a replacement for genetic testing as they can sometimes be less specific which means that a positive IHC result may not always correlate with the presence of a specific genetic alteration. They are also less sensitive compared to molecular tests. Thus, it is important to validate these IHC results with other methods, especially in ambiguous cases. These markers are especially useful in soft tissue tumor pathology, where both benign and malignant neoplasms often harbor defining genetic events that result in protein overexpression or loss. Surrogate markers are particularly useful when soft tissue biopsies are small with scant tumor tissue. Their utility as rapid, cost-effective screening tools is important in modern soft tissue pathology. For CNS neoplasms, the latest WHO classification of CNS neoplasms recommends the use of surrogate IHC markers for molecular classification of gliomas. However, no IHC marker is available for the hallmark 1p/19q codeletion of oligodendrogliomas.

It needs to be further emphasized that while they are often invaluable in low resource settings and countries, they are certainly not a replacement for molecular testing, and there should be extensive efforts even in LMICs to acquire NGS and CGP technologies through public–private partnerships and collaborations.

Strategies for Acquiring and Implementing Latest Innovations in Cancer Care in Low Resource Countries

In poor and developing countries, it is currently very difficult to imagine enhancement of cancer care through molecular testing and personalized treatments. It will require considerable will on part of governments and extensive public–private partnerships and collaborations to develop and sustain infrastructure and manpower, while keeping costs down. Pathologists and clinicians need to convince hospital administrators, philanthropists, and government officials with clear logic and facts and figures about the importance of investing massively and urgently in these areas. Governments alone cannot bring about this transformation and the role of the private sector is critical. Philanthropic support is essential especially for building local capacities. Recent studies from India and Pakistan have shown the potential of such local efforts to develop their own strategic molecular testing panels.[50,51] Thus, in place of more expensive CGP technologies, at least in the initial phase, cheaper and very useful new technologies like targeted Hotspot testing, CRISPR, and portable technologies like point-of-care testing (POCTs) may be acquired as these require considerably less infrastructure development and provide rapid, affordable and reliable testing. Recent advances such as multiplex lateral flow immunoassays detect cancer biomarkers accurately and do not need complex infrastructure. Laboratory technologists and even nurses can be trained to perform POCTs and interpret them and thus cover the shortage of pathologists. Thus, these technologies can be acquired and implemented as the first phase of a phased implementation strategy with initial focus on developing affordable, low cost, sensitive, portable and robust molecular diagnostic tests, which can be performed even by non-specialists, followed by the acquisition of NGS and CGP in a later phase. However, even these low-cost initiatives will require sustained financial support and developing strong public-private collaborations will be extremely important. It will also be very important to convince governments to legislate andenact laws urgently for regulatory oversight and approval of molecular testing and molecular-based therapies, and to establish regulatory bodies for this purpose. Establishment of regional and national molecular testing centers by public–private partnership can be a viable strategy for LMICs. The acquisition and use of DP can allow pathologists in LMICs to get remote consultations from international experts.

Conclusion

Recent advances are changing the practice of oncology. Personalized oncology demands personalized pathology. The core of precision cancer care is the optimization of therapeutic benefits for cancer patients by comprehensive genomic profiling of malignant tumours. Pathology is acquiring an ever-expanding role in precision oncology critical to all aspects of cancer care. Pathologists in general, and those working in developing countries and low resource settings in particular, need to prepare themselves for their expanding roles, and adapt their practices accordingly. In these settings, a strong role for governments and robust collaboration between public and private sectors will be essential to provide financial backing for acquiring and sustaining latest technologies such as NGS and CRISPR, training and retaining manpower, keeping costs low, and ensuring the availability of advanced testing and latest personalized treatments for even the poorest patients.

Disclosure

The authors report no conflicts of interest in this work.

References

1. FDA News Release. FDA allows marketing of first whole slide imaging system (Philips IntelliSite pathology solution-PIPS) for digital pathology. 2017.
2. McGenity C, Clarke EL, Jennings C, et al. Artificial intelligence in digital pathology: a systematic review and meta-analysis of diagnostic test accuracy. *NPJ Digit Med*. 2024;7(1):114. PMID: 38704465; PMCID: PMC11069583. doi:10.1038/s41746-024-01106-8

3. Sharma S, George P, Waddell N. Precision diagnostics: integration of tissue pathology and genomics in cancer. *Pathology*. 2021;53(7):809–817. PMID: 34635323. doi:10.1016/j.pathol.2021.08.003
4. Albitar M. The role of pathology in precision medicine. *Hematopathology*. 2019;3(2):36–40.
5. Masood S. The changing role of pathologists from morphologists to molecular pathologists in the era of precision medicine. *Breast J*. 2020;26 (1):27–34. PMID: 31876097. doi:10.1111/tbj.13728
6. Vranic S, Gatalica Z. The role of pathology in the era of personalized (Precision) medicine: a brief review. *Acta Med Acad*. 2021;50(1):47–57. PMID: 34075763. doi:10.5644/ama2006-124.325
7. Souza da Silva R, Pinto R, Cirnes L, Schmitt F. Tissue management in precision medicine: what the pathologist needs to know in the molecular era. *Front Mol Biosci*. 2022;9:983102. PMID: 36387281; PMCID: PMC9644376. doi:10.3389/fmolb.2022.983102
8. Xu X, Zhao W, Liu C, et al. The residual cancer burden index as a valid prognostic indicator in breast cancer after neoadjuvant chemotherapy. *BMC Cancer*. 2024;24(1):13. PMID: 38166846; PMCID: PMC10762907. doi:10.1186/s12885-023-11719-z
9. Yau C, Osdoit M, van der Noordaa M, et al. Residual cancer burden after neoadjuvant chemotherapy and long-term survival outcomes in breast cancer: a multicentre pooled analysis of 5161 patients. *Lancet Oncol*. 2022;23(1):149–160. PMID: 34902335; PMCID: PMC9455620. doi:10.1016/S1470-2045(21)00589-1
10. Symmans WF, Yan C, Chen -Y-Y, et al. Assessment of residual cancer burden and event free survival in neoadjuvant treatment for high risk breast cancer. An analysis of data from the I-SPY2 randomized clinical trial. *JAMA Oncol*. 2021;7(11):1654–1663. doi:10.1001/jamaoncol.2021.3690
11. Wang W, Liu Y, Zhang H, et al. Prognostic value of residual cancer burden and Miller-Payne system after neoadjuvant chemotherapy for breast cancer. *Gland Surg*. 2021;10(12):3211–3221. PMID: 35070881; PMCID: PMC8749085. doi:10.21037/gs-21-608
12. Ryan R, Gibbons D, Hyland JM, et al. Pathological response following long-course neoadjuvant chemoradiotherapy for locally advanced rectal cancer. *Histopathology*. 2005;47(2):141–146. PMID: 16045774. doi:10.1111/j.1365-2559.2005.02176.x
13. Allison KH, Hammond ME, Dowsett M, et al. Estrogen and Progesterone receptor testing in breast cancer: ASCO/CAP guideline update. *J Clin Oncol*. 2020;38(12):1346–1366. doi:10.1200/JCO.19.02309
14. Ghlichloo I, Jackson W, Fadare O. The effect of prolonged cold ischemia time on breast cancer biomarker expression after neoadjuvant chemotherapy. *Pathol Res Pract*. 2025;266:155781. doi:10.1016/j.prp.2024.155781
15. Suganuma N, Matsubara Y, Takahashi A, et al. Impact of warm ischemia time on HER2 expression in breast cancer surgical specimens. *Anticancer Res*. 2024;44(12):5225–5230. doi:10.21873/anticanres.17350
16. Tsimberidou AM, Kahle M, Vo HH, Baysal MA, Johnson A, Meric-Bernstam F. Molecular tumor boards - current and future considerations for precision oncology. *Nat Rev Clin Oncol*. 2023;20(12):843–863. PMID: 37845306. doi:10.1038/s41571-023-00824-4
17. Ballatore Z, Bozzi F, Cardea S, et al. Molecular tumour board (MTB): from standard therapy to precision medicine. *J Clin Med*. 2023;12(20):6666. PMID: 37892804; PMCID: PMC10607087. doi:10.3390/jcm12206666
18. Volders PJ, Aftimos P, Dedeurwaerdere F, et al. A nationwide comprehensive genomic profiling and molecular tumor board platform for patients with advanced cancer. *NPJ Precis Oncol*. 2025;9(1):66. PMID: 40065106; PMCID: PMC11893761. doi:10.1038/s41698-025-00858-0
19. Pankiw M, Brezden-Masley C, Charames GS. Comprehensive genomic profiling for oncological advancements by precision medicine. *Med Oncol*. 2023;41(1):1. PMID: 37993657. doi:10.1007/s12032-023-02228-x
20. Hung LJ, Huang CY, Tung KC, et al. Comprehensive genomic profiling in multiple cancer types: a comparative analysis of the National Biobank consortium of Taiwan and clinical practice cohorts. *J Formos Med Assoc*. 2025;124(9):830–838. PMID: 39244401. doi:10.1016/j.jfma.2024.09.001
21. Gu J, Taylor CR. Practicing pathology in the era of big data and personalized medicine. *Appl Immunohistochem Mol Morphol*. 2014;22(1):1–9. PMID: 24326463; PMCID: PMC4206549. doi:10.1097/PAI.0000000000000022
22. Chang YS, Ojcius DM. Advancing cancer diagnosis and treatment: integrating molecular biomarkers and emerging technologies. *Biomed J*. 2025;48(1):100831. PMID: 39880303; PMCID: PMC11871436. doi:10.1016/j.bj.2025.100831
23. Angerilli V, Galuppini F, Pagni F, Fusco N, Malapelle U, Fassan M. The role of the pathologist in the next-generation era of tumor molecular characterization. *Diagnostics*. 2021;11(2):339. PMID: 33670699; PMCID: PMC7922586. doi:10.3390/diagnostics11020339
24. Kuehn JC, Metzger P, Neidert N, et al. Comprehensive genetic profiling and molecularly guided treatment for patients with primary CNS tumors. *NPJ Precis Oncol*. 2024;8(1):180. PMID: 39143272; PMCID: PMC11324882. doi:10.1038/s41698-024-00674-y
25. Ahmed AA, Abouzaid M, Kaczmarek E. Deep learning approaches in Histopathology. *Cancers*. 2022;14(21):5264. doi:10.3390/cancers14215264
26. Shafi S, Parwani AV. Artificial intelligence in diagnostic pathology. *Diagn Pathol*. 2023;18(1):109. doi:10.1186/s13000-023-01375-z
27. Waqas A, Bui MM, Glassy EF, et al. Revolutionizing digital pathology with the power of generative artificial intelligence and foundation models. *Lab Invest*. 2023;103(11):100255. doi:10.1016/j.labinv.2023.100255
28. Zhang DY, Venkat A, Khasawneh H, Sali R, Zhang V, Pei Z. Implementation of digital pathology and artificial intelligence in routine pathology practice. *Lab Invest*. 2024;104(9):102111. doi:10.1016/j.labinv.2024.102111
29. Ahuja S, Zaheer S. Advancements in pathology: digital transformation, precision medicine, and beyond. *J Pathol Inform*. 2024;16:100408. PMID: 40094037; PMCID: PMC11910332. doi:10.1016/j.jpi.2024.100408
30. Kim JS, Lee JH, Yeon Y, et al. Predicting Nottingham grade in breast cancer digital pathology using a foundation model. *Breast Cancer Res*. 2025;27(1):58. doi:10.1186/s13058-025-02019-4
31. Ji J, Duan F, Liao Q, et al. Artificial intelligence-based pathology to assist prediction of neoadjuvant therapy responses for breast cancer. *Cancer Med*. 2025;14(15):e71132. doi:10.1002/cam4.71132
32. FDA News Release. Roche granted FDA breakthrough device designation for first AI-driven companion diagnostic VENTANA TROP2 for non-small cell lung cancer. 2025.
33. FDA News Release. FDA grants 510 (k) clearance to Ibex prostate detect AI for prostate cancer. 2025.
34. FDA News Release. PathAI receives U.S. FDA breakthrough device designation for PathAssist Derm, an AI-powered pathology solution to transform Dermatopathology workflow. 2026.
35. FDA News Release. FDA expands labels for Roche's PATHWAY HER2 (4B5) test and VENTANA HER2 Dual ISH DNA Probe Cocktail, which can now be used to identify HER2-positive metastatic breast cancer patients who could be eligible for ENHERTU. 2025.
36. Kim H, Park KU. Clinical circulating tumor DNA testing for precision oncology. *Cancer Res Treat*. 2023;55(2):351–366. PMID: 36915242; PMCID: PMC10101787. doi:10.4143/crt.2022.1026

37. Bartolomucci A, Nobrega M, Ferrier T, et al. Circulating tumor DNA to monitor treatment response in solid tumors and advance precision oncology. *NPJ Precis Oncol*. 2025;9(1):84. PMID: 40122951; PMCID: PMC11930993. doi:10.1038/s41698-025-00876-y
38. Stadler JC, Belloum Y, Deitert B, et al. Current and future clinical applications of ctDNA in immuno-oncology. *Cancer Res*. 2022;82(3):349–358. PMID: 34815256; PMCID: PMC9397642. doi:10.1158/0008-5472.CAN-21-1718
39. Ren C, Liu J, Hornicek FJ, Yue B, Duan Z. Advances of SS18-SSXfusion gene in synovial sarcoma: emerging novel functions and therapeutic potentials. *Biochim Biophys Acta Rev Cancer*. 2024;1879(6):189215. doi:10.1016/j.bbcan.2024.189215
40. Doyle LA, Moller E, Cin PD, Fletcher CDM, Mertens F, Hornick JL. MUC4 is a highly sensitive and specific marker for low-grade fibro-myxoid sarcoma. *Am J Surg Path*. 2011;35(5):733–741. doi:10.1097/PAS.0b013e318210c268
41. Hou X, Shi W, Luo W, et al. FUS::DDIT3 fusion protein in the development of myxoid liposarcoma and possible implications for therapy. *Biomolecules*. 2024;14(10):1297. doi:10.3390/biom14101297
42. Antonescu CR, Suurmeijer AJH, Zhang L, et al. Molecular characterization of Inflammatory fibroblastic tumors with frequent ALK and ROS1 fusions and rare novel RET gene rearrangement. *Am J Surg Pathol*. 2015;39(7):957–967. doi:10.1097/PAS.0000000000000404
43. Jung H, Kim H-N, Jang YJ, Park C-K, Ha S-Y. CAMTA-1 expression in 24 cases of hepatic epithelioid hemangioendothelioma in a single institution: diagnostic utility for differential diagnosis from hepatic angiosarcoma. *In vivo*. 2019;33(6):2293–2297. doi:10.21873/invivo.11736
44. Yoshida A, Sekine S, Tsuta K, Fukayama M, Furuta K, Tsuda H. NKX2.2 is a useful immunohistochemical marker for Ewing sarcoma. *Am J Surg Pathol*. 2012;36(7):993–999. doi:10.1097/PAS.0b013e31824ee43c
45. Shrivastava K, Jain S. Surrogate immunohistochemistry markers in adult gliomas – experience in a tertiary care hospital. *J Lab Physicians*. 2025;17:18–25. doi:10.25259/JLP_152_2024
46. Dono A, Pichardo-Rojas D, Mendoza Mora L, et al. MTAP immunohistochemistry as a surrogate marker of CDKN2A loss in brain tumors: a meta-analysis and literature review. *J Neuropathol Exp Neurol*. 2025;84(7):600–610. PMID: 40249413; PMCID: PMC12199257. doi:10.1093/jnen/nlaf033
47. Sharma S, Mathur K, Mittal A, Mukta M, Jindal A, Kumar M. Study of surrogate immunohistochemical markers IDH1, ATRX, BRAF V600E, and p53 mutation in astrocytic and oligodendroglial tumors. *Indian J Neurosurg*. 2023;12(02):137–146. doi:10.1055/s-0042-1743265
48. Vij M, Cho BB, Yokoda RT, et al. P16 immunohistochemistry is a sensitive and specific surrogate marker for CDKN2A homozygous deletion in gliomas. *Acta Neuropathol Commun*. 2023;11(1):73. PMID: 37138345; PMCID: PMC10155323. doi:10.1186/s40478-023-01573-2
49. Sung YN, Kim D, Kim J. p53 immunostaining pattern is a useful surrogate marker for TP53 gene mutations. *Diagn Pathol*. 2022;17(1):92. PMID: 36471402; PMCID: PMC9720942. doi:10.1186/s13000-022-01273-w
50. Qazi R, Islam A, Akhter A, Phung T. Clinical impact of in-house molecular testing of solid tumors in resource-limited settings: a pilot study in Pakistan. *Cancer Genetics*. 2025;298–299:S15. doi:10.1016/j.cancergen.2025.10.036
51. Biswas B, Pai T, Raut N, et al. Expert consensus on diagnosis and molecular testing strategies for non-small cell lung cancer in India. *Ind J Med Paed Oncol*. 2025.