Review Article

Evolving role of clinical laboratories in precision medicine: a narrative review

Shahad Arikat[1,2], **Muhammad Saboor**[1,2]

[1]Research Institute for Medical and Health Sciences, University of Sharjah, Sharjah, United Arab Emirates; [2]Department of Medical Laboratory Sciences, College of Health Sciences, University of Sharjah, Sharjah, United Arab Emirates

Contributions: (I) Conception and design: Both authors; (II) Administrative support: None; (III) Provision of study materials or patients: None; (IV) Collection and assembly of data: None; (V) Data analysis and interpretation: None; (VI) Manuscript writing: Both authors; (VII) Final approval of manuscript: Both authors.

Correspondence to: Muhammad Saboor, PhD. Department of Medical Laboratory Sciences, College of Health Sciences, University of Sharjah, University City, Sharjah, United Arab Emirates; Research Institute for Medical and Health Sciences, University of Sharjah, Sharjah, United Arab Emirates. Email: M.Ahmed@sharjah.ac.ae.

Background and Objective: Precision medicine (PM) represents a transformative approach in healthcare, tailoring treatments based on individual genetic and molecular profiles. This shift from a generalized to personalized care model revolutionizes healthcare. Here, we aim to explore the evolving role of clinical laboratories within PM in reshaping healthcare delivery and enhancing patient-specific treatments.

Methods: Our literature search encompassed comprehensive databases such as PubMed, Scopus, and Web of Science, utilizing keywords like "precision medicine", "clinical laboratories", and "personalized medicine". We meticulously screened articles published until November 2023 to gather relevant studies, narrative reviews, and meta-analyses. Additionally, we scrutinized key journals and references within retrieved articles to ensure inclusivity and depth in our analysis of the evolving role of clinical laboratories in PM.

Key Content and Findings: Clinical laboratories stand as crucial pillars in the execution of direct, personalized diagnostic tests and therapies within the PM framework. Their multifaceted role extends beyond disease diagnosis and risk assessment, encompassing the development of targeted therapeutic strategies. This review underscores the instrumental nature of these laboratories in facilitating specialized treatments and substantially improving patient outcomes.

Conclusions: This research accentuates the escalating significance of clinical laboratories in the burgeoning domain of PM. Their pivotal contribution as hubs for data analysis and collaborative efforts with healthcare experts underscores their pivotal role in shaping the future of healthcare delivery. The synergy between clinical laboratories and healthcare professionals is paramount in pushing the boundaries of PM and enhancing patient-centric care.

Keywords: Laboratory medicine; clinical laboratories; precision medicine (PM)

Received: 18 December 2023; Accepted: 30 January 2024; Published online: 12 April 2024.

doi: 10.21037/jlpm-23-96

View this article at: https://dx.doi.org/10.21037/jlpm-23-96

Introduction

Overview of precision medicine (PM)

PM, also known as personalized medicine, is an innovative approach to healthcare that customizes medical treatment and interventions to the individual characteristics of each patient. It takes into account a person's unique genetic makeup, environmental influences, lifestyle factors, and other relevant information to customize strategies for disease prevention, diagnosis, and treatment (1). The goal of PM is to enhance treatment effectiveness, minimize side effects, and improve overall patient outcomes by

considering the specific attributes that make each individual distinct. This approach contrasts with more traditional medical practices that may adopt a one-size-fits-all approach (2). Additionally, PM involves the use of advanced computational tools to integrate and analyze heterogeneous data from various sources, including basic science, clinical trials, personal records, environmental factors, and population health records. Connections are drawn between the collected information to elucidate biological processes, define disease mechanisms, and develop more precise diagnostics, therapeutics, and preventive measures. This personalized approach to medicine holds the potential to revolutionize healthcare by improving treatment efficacy, minimizing side effects, and ultimately enhancing patient outcomes (2-5). By adopting a proactive rather than reactive stance towards disease diagnosis and management, PM empowers patients to take a more active role in their healthcare journey. Although still in its nascent stages, PM harbors immense potential to redefine the mechanisms through which diseases are diagnosed, treated, and prevented. This approach is not just a future possibility but is gradually becoming an integral part of contemporary healthcare, promising a new era of highly personalized and effective medical interventions.

Rationale of the study

Clinical laboratories are healthcare facilities that provide a wide range of laboratory procedures which aid physicians in carrying out diagnosis, treatment, and patient management. These laboratories play a vital role in PM, as they provide the services needed to collect relevant patient information needed to design personalized treatment plans. Amongst these services include diagnostic testing, genomic sequencing, and other available laboratory tests that may extend to research, drug development, treatment monitoring (6). Adequate funding is an essential element needed to extend the line between PM and clinical laboratories. Greater number of tests being available to collect patient information leads to the accumulation of more data for subsequent analysis in both healthcare and research settings (7).

Many clinical laboratories provide patients with genetic testing to identify their risk for acquiring a disease. Additionally, genomic sequencing may also be provided which involves the identification of genetic mutations within an individual's genome (8). The information generated by these tests aid physicians in determining the criteria needed for current and future diagnostic practices, treatment plans and patient monitoring programs. It may also be utilized in pharmacogenomic testing to determine the most effective drug treatment for each patient (9-11). Thus, highlighting the essential role of clinical labs in acting as a bridge between patients and their most optimum healthcare strategies.

Objective

The field of PM is undergoing rapid advancements, continually introducing novel technologies and methodologies. For instance, the emergence of next-generation sequencing (NGS) has revolutionized genome sequencing, enabling comprehensive genomic analysis at greater cost-effective rates (12,13). Consequently, the increased availability of genomic data has facilitated the discovery of novel disease-related genetic markers (14). Another critical advancement in PM involves the development of data integration and analytical tools (15). These tools are utilized to combine patient data from various sources, including electronic health records (EHRs), genomic and clinical trial data. The subsequent connections drawn between combined data fosters new perspectives on disease etiology and treatment responses (16). Ultimately, this assimilated knowledge can be harnessed to devise tailored treatment regimens for individual patients. Notably, clinicians can leverage this information to determine the optimal pharmaceutical interventions for specific patients and tailor personalized monitoring strategies accordingly. The more data and information that are collected and thus connected, the better scientists will understand health, further ensuring that patients receive adequate treatment, monitoring, and care for many generations, increasing patient satisfaction and prolonging expected lifespans. This review seeks to find out the role of clinical laboratories in the dynamic landscape of PM.

By exploring rapid advancements, including novel technologies such as NGS and the development of data integration tools, we aim to highlight how these innovations facilitate the discovery of disease-related genetic markers and enable comprehensive patient data analysis. Furthermore, our objective is to underscore how the amalgamation of diverse patient data sources fosters new insights into disease etiology and treatment responses. Through this exploration, our aim is to explore the role of clinical laboratories in enabling tailored treatment regimens and personalized monitoring strategies, ultimately enhancing patient care and outcomes within the realm of PM.

Table 1 The search strategy summary

Items	Specification
Date of search	September 8, 2023 to October 15, 2023
Databases and other sources searched	PubMed, Scopus, Web of Science, Embase, Google Scholar
Search terms used	Precision medicine, personalized medicine, individualized medicine stratified medicine targeted therapy, biomarkers, pharmacogenomics, and genomic medicine
Timeframe	Until November 2023
Inclusion exclusion criteria	For inclusion criteria, a thorough search encompassed articles specifically addressing precision medicine and personalized medicine. The articles were searched using precision medicine, personalized medicine, individualized medicine stratified medicine targeted therapy, biomarkers, pharmacogenomics, and genomic medicine. The selected articles were required to provide in-depth insights into the principles, applications, and advancements within the field. Publications not available in the English language were excluded to ensure accessibility for a wider audience
Selection process	The literature selection process was meticulously executed by S.A. Consensus was achieved through collaborative discussions, where discrepancies were resolved through rigorous examination and collective agreement, ensuring the inclusion of high-quality and pertinent literature in the review

The primary audience targeted by the review article encompasses a diverse range of stakeholders within the healthcare domain, including healthcare professionals, researchers, and policymakers. Healthcare professionals, including clinicians and laboratory experts, will find valuable insights into the evolving role of clinical laboratories in PM, aiding them in staying abreast of advancements that directly impact their practice. Researchers engaged in the fields of PM, laboratory sciences, and healthcare innovation will discover nuanced discussions and comprehensive literature synthesis, fostering a deeper understanding of the subject for further investigation. Policymakers involved in shaping healthcare policies and strategies will benefit from the review's insights, guiding them in formulating evidence-based decisions that align with the transformative landscape of PM. The intended audience, therefore, encompasses a spectrum of professionals crucial to advancing healthcare practices and policies in the era of PM. We present this article in accordance with the Narrative Review reporting checklist (available at https://jlpm.amegroups.org/article/view/10.21037/jlpm-23-96/rc).

Methods

The literature search encompassed articles published up to the current date without any restrictions on the starting date, ensuring a comprehensive inclusion of relevant studies across the evolution of PM. English language articles were included to ensure accessibility and comprehensibility of gathered data. Our search targeted various study designs, including original research articles, narrative reviews, meta-analyses, and clinical trials. This inclusive approach aimed to gather diverse perspectives and insights on the role of clinical laboratories in PM. We conducted a thorough search across key databases, including PubMed, Scopus, Web of Science, and other pertinent scientific repositories. These databases were chosen for their extensive coverage of biomedical literature, ensuring a comprehensive collection of relevant studies and reviews within the field of PM. *Table 1* depicts details of literature search and databases.

Early developments in PM

Though PM is a relatively new field, its premise has been around for many years. Its large-scale implementation has only recently been possible due to major advancements in modern technology. During the 1900s, scientists discovered that certain diseases, such as sickle cell anemia (SCA) and hemophilia, were caused by specific genetic mutations (17,18). This led to the development of genetic testing to identify individuals at risk for developing such diseases. A similar breakthrough was seen in the 1970s, when scientists developed recombinant DNA technology to facilitate the isolation and subsequent manipulation of various genes (19,20), thus guiding the development of new diagnostic tests and treatment for many genetic disorders. Researchers

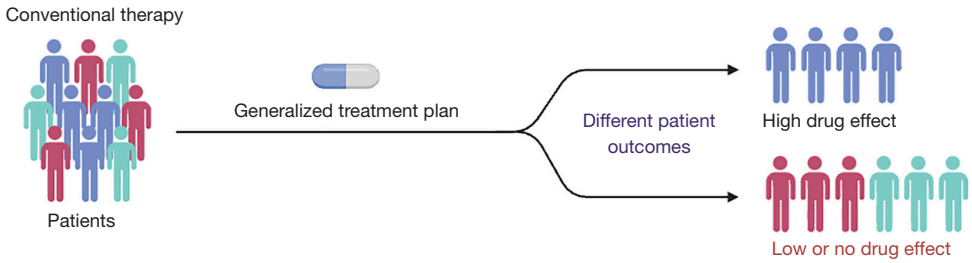

Figure 1 Conventional treatment methodology.

began mapping the human genome in the 1990s under the title of the "Human Genome Project", with findings contributing to our current understanding of human genetics (21).

Traditional approaches to healthcare utilize obvious patient symptoms, the conduction of standard diagnostic tests as well as the issuing of common drugs (*Figure 1*). In the past, medications were typically developed to target single conditions, without considering the potential impact of genetic variations and comorbidities on a patient's response to treatment. Clinical trials, which assessed the safety and effectiveness of these medications, often recruited patients based on specific criteria that did not account for genetic diversity or the presence of multiple health conditions (22). Real-world data encompasses patient information gathered beyond clinical trials, including data from case reports, medical histories, prescription records and laboratory test results. Most of which being data that is directly provided by clinical labs, further highlighting their role in the development of PM. EHRs have enabled the electronic recording, storage, sharing, and analysis of this wealth of patient data (23,24). Access to such extensive and deidentified patient databases has empowered scientists to gain profound insights that were previously obscured by the limited sample sizes in clinical trials (24).

Emerging technologies in PM

Next generation sequencing, mass spectrometry (MS), artificial intelligence (AI), microfluidics, digital pathology, telepathology and point-of-care testing (POCT) are a few examples of emerging technologies being implemented in clinical laboratories to facilitate personalized patient care (25). As these technologies continue to develop and become more widely available, they are expected to have significant implications on the diagnosis and treatment of various deadly diseases.

Next generation sequencing

NGS is a high-throughput DNA sequencing technology that allows for the rapid and accurate sequencing of millions of DNA fragments (26). NGS has completely revolutionized the field of genomics, making it possible to sequence entire genomes, transcriptomes, and epigenomes at relatively low costs and fast rates. These technologies are based upon a variety of different principles that share a common goal of parallelizing the sequencing process. This is achieved by dividing the DNA sample into millions of small fragments, that are then individually sequenced (26). The individual sequencing reads are then assembled into a complete DNA sequence. NGS technologies are preferred over the traditional Sanger sequencing technique due to their lower overall costs, greater accuracy and increased versatility (27). NGS has facilitated major discoveries in the field of genomics, including the identification of new genes, the characterization of genetic variation, and the development of new diagnostic tests (28). NGS is also being used to develop new personalized treatments for cancer and other diseases (12,29).

NGS has been utilized within clinical practices to identify cancer-related genetic mutations (cancer genomics) (29). Diagnosing genetic diseases and determining the genetic variants that cause them provides information needed facilitate genetic counselling for respective patients. This technique has been successfully employed in the diagnosis of cystic fibrosis (CF), SCA and Down syndrome (DS). NGS has also provided invaluable information in cancer drug trials, by identifying the specific genetic mutations causing the tumors to develop resistance to specific treatment plans (29). Additionally, hospitals have employed NGS to identify and characterize many microorganisms, providing data that is useful in the development of new diagnostic tests and treatments for infectious diseases (30). It is a powerful tool that is transforming the field of genomics and

enabling new discoveries in research and clinical practices. As the technology continues to develop and become more affordable, it is likely that NGS will be widely incorporated within clinical laboratories in the foreseeable future.

NGS, while a powerful tool in PM, is not without its limitations. One significant challenge lies in the interpretation of vast amounts of genomic data, as distinguishing clinically relevant variants from incidental findings can be intricate. Additionally, NGS may encounter difficulties in accurately detecting certain types of genetic variations, such as structural variants or repetitive sequences. The cost associated with NGS technologies remains a barrier to widespread implementation, hindering accessibility for some patient populations. Moreover, the potential for errors, including false positives and negatives, necessitates rigorous validation procedures. Ethical concerns surrounding the privacy and security of genomic data also emerge as a critical limitation. Addressing these limitations is paramount to maximizing the utility of NGS in PM and ensuring its effective integration into clinical practice.

MS in clinical laboratories

MS is a powerful analytical technique used to identify and quantify compounds in a sample, based on the mass-to-charge ratio (m/z) of present ions (31,32). MS is used in a wide variety of fields, including clinical chemistry, microbiology, and toxicology. This technique enables the identification and quantification of proteins, peptides, lipids, and carbohydrates (31).

In clinical laboratories, MS is being utilized for diagnostic testing, drug monitoring, personalized medicine and conducting research (33). For example, MS has been used to successfully diagnose inborn errors of metabolism by identifying elevated levels of specific amino acids (34). Additionally, MS is employed to monitor patients' drug and metabolite levels, providing critical information as to the efficacy of the drug delivery system, optimal dosage and adverse effects (35). Moreover, MS can be used to identify the genetic mutations responsible for tumor drug-resistance, thus aiding the drug selection process (36). This tool acts as a conduit for conducting research with its application in studying cancer cell metabolism and identifying disease biomarkers (37,38). MS, while a valuable tool in PM, comes with certain limitations. One challenge lies in the complexity of data interpretation, especially when dealing with intricate proteomic profiles. Identifying and quantifying proteins accurately can be challenging, particularly for low-abundance molecules. Another limitation involves the need for sophisticated instrumentation and expertise, making MS less accessible in certain clinical settings. The technique may also face challenges in detecting post-translational modifications and protein isoforms, potentially impacting the comprehensiveness of the proteomic analysis. Furthermore, standardization of protocols and data analysis methods is crucial to ensure consistency and reproducibility across different studies. Despite these limitations, ongoing advancements in MS technologies and methodologies continue to address these challenges, enhancing its utility in advancing PM applications.

AI

AI is rapidly transforming clinical laboratories, enabling more accurate and efficient diagnostics, personalized medicine, and innovative research (39,40). It is currently being incorporated into clinical laboratories in a variety of ways, including task automation, improving test accuracy, accelerating test developments as well as research breakthroughs (15,39,41).

Notably, AI-powered systems have automated a variety of time consuming and routine tasks in clinical laboratories, such as specimen processing, image analysis, and data entry. This frees up laboratory staff to focus on the more complex tasks needed to improve overall workflow and efficiency. The implementation of AI has been shown to improve the accuracy of diagnostic testing by identifying patterns and anomalies that may be difficult for human technicians to detect (42).

For example, AI-powered systems can be used to identify cancer cells or to detect rare mutations in DNA sequencing data (43,44). AI is also being used to develop new diagnostic tests that are more accurate, sensitive, and less invasive than traditional tests (45,46). AI-based techniques are also being developed to diagnose respiratory disease using less invasive approaches, such as cough samples (47). Moreover, AI has facilitated the progression of personalized patient treatment plans, by analyzing an individual's genetic and molecular profiles while cross-referencing an already available database (*Figure 2*). This form of intelligence allows for large scale analysis of heterogenous patient datasets, identifying new patterns and associations that may lead to medical breakthroughs (40). Automated image analysis in histopathology laboratories has successfully enhanced medical diagnostics (48). Furthermore, AI plays a prominent role in pharmaceutical research, allowing for

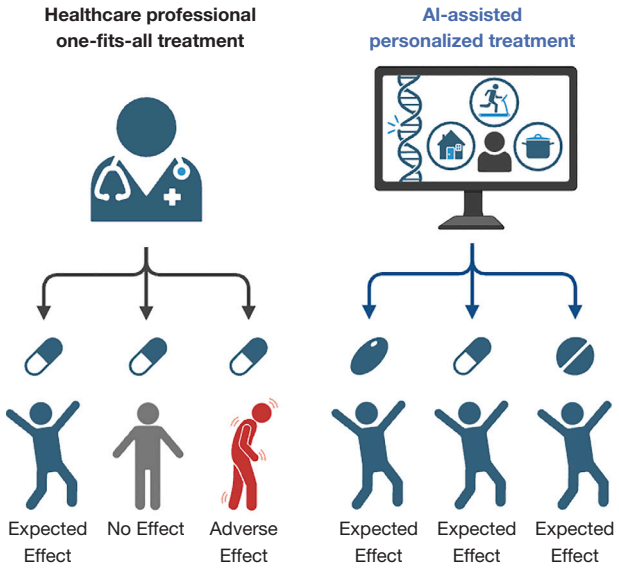

Figure 2 Conventional and AI-assisted personalized treatment. AI, artificial intelligence.

virtual screening and drug designs to be formulated prior to production, facilitating cost-effective manufacturing and efficient drug development programs (49). AI in PM presents transformative potential but is not exempt from limitations. One notable challenge is the need for large, high-quality datasets to train AI algorithms effectively. Limited availability of diverse and comprehensive datasets can hinder the performance and generalizability of AI models. Interpretability and transparency of AI-driven predictions pose additional concerns, as complex models may lack clarity, making it challenging for healthcare professionals to trust and comprehend the underlying decision-making processes. Ethical considerations, including patient privacy and data security, also demand careful attention. Furthermore, the dynamic and evolving nature of healthcare data requires continuous adaptation of AI models to stay relevant. Addressing these limitations is crucial for harnessing the full potential of AI in PM while ensuring its ethical and practical integration into clinical practice.

Proteomics

Proteomics refers to the large-scale study of all expressed proteins (proteoforms) and their interactions (50). This enables the identification of disease-associated proteins, the development of targeted therapies, and the monitoring of patient responses to treatment (51).

Proteomics facilitates the development of PM within clinical laboratories, for fields such as cancer diagnostics, targeted therapies and patient monitoring (51,52). Clinical proteomic studies have been utilized to compare the protein profiles of cancerous tissue samples with those of unaffected controls from the same patient or between patients with varying stages of cancer. This facilitates the identification of potential diagnostic and prognostic biomarkers, respectively (53). Proteomics is also being used to monitor proteins levels associated with cancer progression in the blood, providing insight as to any needed adjustment in treatment plans and provide early detection of recurrence (54). MS-based proteomics is increasingly used in laboratory medicine to identify and quantify biomolecules in biological specimens. It is expanding in biomarker discovery for early detection, prognosis, treatment response prediction, and monitoring. Making these tests more readily available, accessible, and affordable will provide great improvements in various healthcare systems.

Microfluidics refers to technology that allows for the manipulation of fluids at the microscale (55), with microfluidic proteomics being utilized in the development of new diagnostic tests and to perform high-throughput proteomics experiments (56).

Utilization of proteomics in clinical laboratories also harbors certain limitations. One challenge is the inherent dynamic range of protein expression levels, making it difficult to detect low-abundance proteins amid more abundant ones. Sensitivity issues can hinder the comprehensive identification and quantification of proteins in complex biological samples. Additionally, proteomic analyses may face challenges in capturing post-translational modifications and protein isoforms accurately. The need for advanced instrumentation and expertise can be a barrier to widespread adoption, limiting accessibility in certain clinical settings. Standardization of protocols and data analysis methods is crucial to ensure reproducibility and comparability across studies. Overcoming these limitations is essential for unlocking the full potential of proteomics in advancing PM applications.

Protein biomarkers

Protein biomarkers are proteins that are measured in the blood, urine, or other bodily fluids, to detect, diagnose, or monitor a disease (57). As noted with the other applications, they play an increasingly important role in PM by enabling the development of personalized treatment plans and the

monitoring of patient response to treatment. Moreover, early-stage cancer diagnosis is facilitated by the detection of cancer biomarkers, which are also used to diagnose different types of cancer and to monitor patient response to cancer treatment (58). Prostate-specific antigen (PSA) is used to screen for prostate cancer while human epidermal growth factor receptor 2 (HER2) is a marker for breast cancer (59,60). Infectious disease biomarkers such as C-reactive protein (CRP), which detects inflammation during onset of infections and D-dimer levels help diagnose deep vein thrombosis (DVT) and pulmonary embolisms (61,62). B-type natriuretic peptide (BNP) and troponin are examples of cardiovascular disease (CVD) biomarkers used to detect and diagnose heart failure and heart attacks, respectively (63). In addition to their other functions, PSA is also used to monitor the effectiveness of prostate cancer treatment, while CRP is used to monitor the effectiveness of treatment for inflammatory diseases.

Protein biomarkers can be measured in blood samples using immunoassays, MS, microarrays, surface plasmon resonance, reverse phase protein array among others. Blood tests for these biomarkers are widely used in clinical laboratories for disease diagnosis and monitoring (64). Urine biomarker tests are less prevalent but aid in diagnosing kidney disease and urinary tract infections (UTI) (64). Tissue analysis is typically done using immunohistochemistry (IHC) and is useful for diagnosing certain cancers. Measuring protein biomarkers in various body fluids provide physicians with insight as to a patient's disease state and thus facilitates the development of personalized treatment plans and further incorporation of PM in the laboratory setting.

While protein biomarkers play a crucial role in PM, they are not without limitations. One notable challenge lies in the variability of protein expression levels among individuals, making it challenging to establish universal biomarkers applicable to diverse populations. Sensitivity and specificity issues can affect the accuracy of detection, leading to false positives or negatives. The dynamic nature of proteins, influenced by factors such as disease progression and treatment responses, adds complexity to their utility as stable and reliable indicators. Additionally, the identification of clinically relevant biomarkers amidst a multitude of proteins in complex biological samples can be intricate. Standardization of assay methods and result interpretation is essential to ensure consistency across studies. Overcoming these limitations is crucial for harnessing the full potential of protein biomarkers in guiding personalized treatment strategies within the realm of PM.

Applications of PM in clinical laboratories

Genetic testing and diagnosis

Genetic testing can be used to diagnose genetic disorders, cancer, heart disease, neurological disorders as well as infectious diseases (65,66). Its use in diagnosing newborns with conditions such as CF, provides invaluable information for family genetic counseling. Tumor and germline genetic testing has played a critical role in breast cancer management (67). It can also be used to identify people who have a family history of cancer and therefore face an increased risk of developing the disease themselves (68). The integration of genetic testing and personalized treatment plans in PM necessitates careful consideration of ethical dimensions, encompassing patient privacy, equitable access, handling of sensitive data, management of incidental findings, and responsible communication of results to ensure ethical implementation in clinical practice.

Developing new diagnostic tests

PM is driving the development of more accurate diagnostic tests to facilitate earlier disease detection (69). These methodologies are being developed to detect cancer and other diseases using blood or even breath samples. This could lead to earlier and more accurate diagnoses, thus enhancing patient care, satisfaction and outcomes. Liquid biopsies are being utilized for PM in cancer management, such as urologic malignancies, providing earlier cancer diagnoses and monitoring patients response to treatment (70,71).

Monitoring the response of patients to targeted therapies

Targeted therapy is a type of PM that uses drugs to target specific molecules or signaling pathways in cells such as cancer, allowing for a more effective approach with fewer side effects than traditional chemotherapy (72). To identify patients who are likely to benefit from targeted therapy, physicians need to understand the molecular biology of the individual's tumor. Despite scientific evidence supporting dose individualization of oral targeted anticancer therapies, most are still administered using a one-size-fits-all approaches (73). Dose individualization can improve both efficacy and safety and should be considered in all patients treated with these agents (73).

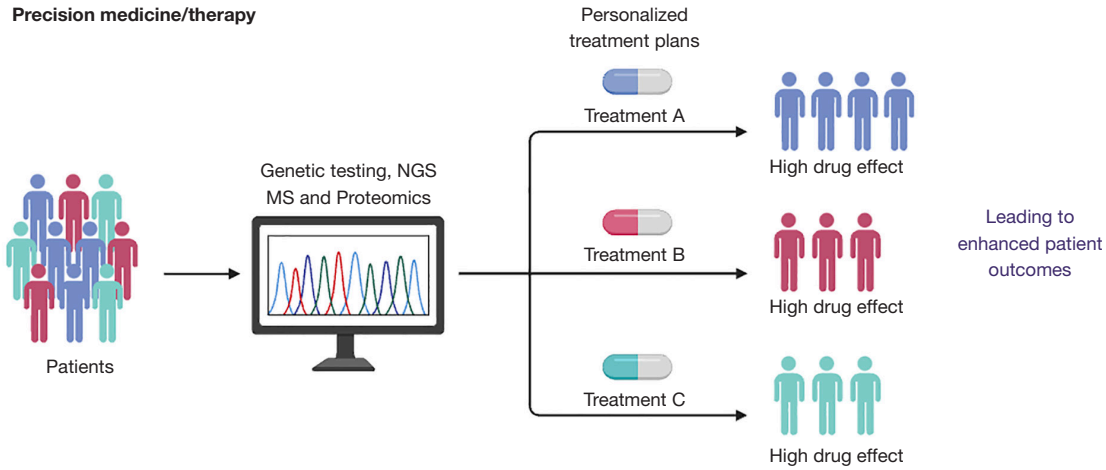

Figure 3 Utilization of precision medicine. NGS, next-generation sequencing; MS, mass spectrometry.

PM in cancer care

AI is being used to develop new PM approaches to cancer care (74). By analyzing large amounts of clinical biodata, AI can help researchers identify personalized treatment targets for each patient. This approach has the potential to improve outcomes for patients with cancer (75). In addition, genomics and PM are making it possible to tailor breast cancer treatment to individual patients, which is leading to better outcomes (76).

Challenges and opportunities for clinical laboratories in PM

Some critics argue that PM is overpromising on its potential to transform patient care (77). They point out that since it is still in its early stages of development, it is not clear how effective it will be in the real world. Additionally, they argue that PM is expensive, and that it may not be accessible to every lab or patient (77).

Implementing PM in clinical laboratories pose several challenges, most notably the rapid rate at which these technologies are being developed. Thus, making it difficult for clinical laboratories, especially those in underdeveloped regions, to keep up-to-date with the latest advancements. This challenge is compounded by the fact that PM is a multidisciplinary field that requires specialized expertise in genetics, bioinformatics, and clinical medicine. Clinical laboratories may need to collaborate with field experts to fully understand and correctly implement these new approaches. Another challenge is the potential up-front test costs, potentially limiting patient or healthcare systems accessibility (77). Additionally, in the dynamic landscape of PM, the convergence of ethical, legal, and social factors intricately shapes its trajectory and impact. Ethical, legal, and social factors are fundamental influencers in PM, guiding the ethical practice, legal frameworks, and societal implications of this transformative approach to healthcare. Ethically, considerations for patient privacy, informed consent, and ethical communication of genetic findings are paramount. Legally, navigating issues related to data ownership, liability, and regulatory compliance establishes the operational framework for PM. Socially, accessibility, and equitable distribution of PM technologies are critical factors influencing healthcare disparities and shaping societal perceptions of genetic information. The intricate interplay of these factors collectively molds the ethical, legal, and societal dimensions of PM, impacting its effectiveness and responsible integration into healthcare systems. Overcoming these challenges demands sustained investment in research, technology, and workforce development, alongside the establishment of standardized and scalable workflows. However, amid these challenges, numerous opportunities arise for clinical laboratories to enhance patient outcomes by adeptly embracing cutting-edge technologies. Looking ahead, the future for clinical laboratories in PM appears promising. Continued evolution in the field positions laboratories is significant in promoting patient-centric methodologies, advancing healthcare outcomes through personalized diagnostics, tailored treatment strategies, and refined patient monitoring protocols (*Figure 3*).

The evolving landscape of PM presents exciting

prospects for future developments that could significantly impact clinical laboratories. Anticipated trends include the integration of advanced technologies such as AI for enhanced data analysis, the expansion of multi-omics approaches for comprehensive patient profiling, and the increasing utilization of liquid biopsy techniques for non-invasive molecular diagnostics. Additionally, the growing emphasis on real-time, personalized treatment strategies may necessitate the establishment of more streamlined and collaborative frameworks between clinical laboratories and healthcare providers. These anticipated trends collectively signal a dynamic future for PM, with clinical laboratories at the forefront of translating innovative approaches into practical and impactful healthcare solutions.

Emphasizing the critical role of collaboration, it is imperative to reiterate that the successful implementation of PM hinges upon robust partnerships between clinical laboratories and healthcare stakeholders. Clinical laboratories serve as central hubs for generating, analyzing, and interpreting patient data, making collaboration essential for seamless integration into healthcare workflows. Close coordination ensures that laboratory insights are effectively translated into actionable treatment strategies, optimizing patient outcomes. This collaborative synergy also facilitates the adaptation of evolving technologies and methodologies, fostering a dynamic and responsive PM framework within the broader healthcare ecosystem. As PM continues to advance, reinforcing and nurturing these collaborations becomes essential for achieving the full potential of personalized and effective patient care.

Conclusions

Clinical laboratories play a crucial role in the evolving landscape of PM. By leveraging innovative diagnostic tests and genomic sequencing technologies, clinical laboratories enable the identification of genetic factors that underlie a plethora of diseases. This information is utilized to develop personalized treatment strategies that improve patient outcomes. To fully realize the potential of PM, clinical laboratories must proactively invest in cutting-edge technologies and forge collaborative partnerships with healthcare stakeholders. By embracing innovation and fostering strategic alliances, clinical laboratories can secure a leading role in the ongoing evolution and integration of PM. This will ensure optimal patient care and treatment outcomes, while also advancing the frontiers of healthcare delivery.

Acknowledgments

Funding: None.

Footnote

Reporting Checklist: The authors have completed the Narrative Review reporting checklist. Available at https://jlpm.amegroups.org/article/view/10.21037/jlpm-23-96/rc

Peer Review File: Available at https://jlpm.amegroups.org/article/view/10.21037/jlpm-23-96/prf

Conflicts of Interest: Both authors have completed the ICMJE uniform disclosure form (available at https://jlpm.amegroups.org/article/view/10.21037/jlpm-23-96/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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doi: 10.21037/jlpm-23-96
Cite this article as: Arikat S, Saboor M. Evolving role of clinical laboratories in precision medicine: a narrative review. J Lab Precis Med 2024;9:17.