REVIEW ARTICLE

Personalized Medicine: Bridging the Gap between Genetics and Clinical Practice

Mohd Imran[1,2], Abida[1,2], Hayet Ben Khaled[1], Abdulrahman Thamer Alanazi[3], Mohammed Amer Alanazi[3], Khalid Adnan Alshammari[3], Mashari Abdullah Alenezi[3], Hina Skhawat[4], Muhammad Skhawat Ali[4], Muhammad Irfan Siddique[5]

[1]Department of Pharmaceutical Chemistry, College of Pharmacy, Northern Border University, Rafha, Saudi Arabia, [2]Center for Health Research, Northern Border University, Arar, Saudi Arabia, [3]College of Pharmacy, Northern Border University, Rafha, Saudi Arabia, [4]Department of Basic Sciences, Applied College, Northern Border University, Rafha, Saudi Arabia, [5]Department of Pharmaceutics, College of Pharmacy, Northern Border University, Rafha, Saudi Arabia

Abstract

Personalized medicine is a groundbreaking approach to healthcare that tailors' treatment each patient based on their unique genetic makeup, environment, and lifestyle. A key part of this approach is pharmacogenomics, which looks at how genetic differences can affect and how patients respond to medications. By understanding how genes influence drug metabolism and effectiveness, clinicians can choose the best medications and dosages for individual patients, potentially improving treatment outcomes and minimizing side effects. This review delves into the current landscape of personalized medicine and explores how pharmacogenomics plays a role in drug response, the opportunities and challenges of bringing personalized medicine into mainstream healthcare, and where this innovative field is headed in the future. Although personalized medicine has made great strides, challenges still exist, including ethical issues, questions around cost-effectiveness, and the need for clear guidelines. Yet, with continued investment in research and addressing these hurdles, personalized medicine has the potential to significantly improve patient outcomes and transform the way healthcare is delivered.

Key words: Cost-cutting, healthcare system, patient outcomes, personalized medicine, pharmacogenomics

INTRODUCTION

With personalized medicine, the healthcare industry is undergoing a paradigm shift from a one-size-fits-all strategy to one that is more proactive and customized.[1] Fundamentally, Personalized medicine refers to a medical approach that leverages an individual's genetic information to guide decisions related to the prevention, diagnosis, and treatment of diseases.[2] This method acknowledges that each person reacts differently to drugs and treatments due to their own genetic composition and exposures to the environment.[3] For example, studies indicate that nearly 90% of the population exhibits at least one genetic variant associated with drug response, highlighting the widespread applicability of pharmacogenomics.[4] Pharmacogenomics is one of the core principles of personalized medicine and is the scientific discipline concerned with how genetic factors affect drug metabolism.[5] Since differences in the response to drugs are reflected in terms of genetics, it is possible for such clinicians to determine the best drugs and dosage, thus enhancing the possibility for a better treatment and reducing the incidence of side effects.[6]

The field of personalized medicine has rapidly grown over the past decade after the start of the Human Genome Project in 2003, which provided a detailed blueprint of the genetic basis of human health and disease.[3] Genomic advancements, together with the emergence of large genomic databases have made it possible to identify genes that are linked to pharmacogenomics response.[7] These findings have paved the way for the development of targeted therapies and

Address for correspondence:
Muhammad Irfan Siddique, Department of Pharmaceutics, College of Pharmacy, Northern Border University, Rafha, Saudi Arabia.
E-mail: mirfan.siddique@gmail.com

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diagnostic tools that are revolutionizing clinical practice across multiple medical fields.[8] Pharmacogenomics allows healthcare providers to tailor drug selection and dosage to an individual's genetic profile, improving treatment effectiveness and reducing adverse effects.[9] For instance, research has shown that polymorphisms in genes including CYP2D6 and CYP2C9 can highly affect the pharmacokinetics of some drugs and, thus, either contribute to the inefficiencies of drugs or to adverse drug reaction (ADR).[10] This move from standardized treatments to personalized, patient-focused care is reshaping modern medicine.[11]

The advantages of personalized medicine are considerable. By customizing treatment plans to fit each patient's unique needs, healthcare providers can achieve better treatment outcomes, lower healthcare costs, and increase patient satisfaction.[12] A 2023 meta-analysis published in the demonstrated that personalized medicine approaches can result in a 20% decrease in mortality rates compared to conventional treatments. Moreover, personalized medicine can help reduce health disparities by ensuring that patients from various backgrounds receive care tailored to their genetic profiles, offering more equitable and effective treatment.[13]

However, despite the progress made in understanding the human genome, there remains a significant gap between the wealth of genetic knowledge and its routine application in clinical practice. Translating complex genetic data into actionable clinical insights is essential for personalized medicine to reach its full potential.[11] This transition involves not only technological innovation but also developing clinical frameworks, educating healthcare providers, and addressing regulatory and ethical challenges.[6] The ability to integrate genetic knowledge into everyday medical practice represents the core challenge and opportunity of personalized medicine in modern healthcare.[14]

Advances in Genetics Driving Personalized Medicine
Human genetics play a fundamental role in personalized medicine, providing critical insights into the biological foundation that makes each individual unique. The human genome, comprising around 3 billion DNA base pairs, contains the essential genetic instructions for human development, physiology, and overall health.[14] One of the most transformative tools in this field is whole-genome sequencing (WGS), which allows for the comprehensive analysis of an individual's entire DNA.[15] This technology has revolutionized genetics by offering a detailed view of both the coding and non-coding regions of the genome, as well as regulatory sequences and structural variants. With WGS, clinicians can identify both common and rare genetic variants that may contribute to disease or influence how a patient responds to treatment. Since the completion of the Human Genome Project, the cost of sequencing a human genome has dropped dramatically, making it increasingly viable for clinical use.[16]

The application of WGS has led to the identification of numerous genetic markers associated with a wide range of diseases, including cancer, cardiovascular conditions, and neurodegenerative disorders.[15] These discoveries have facilitated the development of targeted therapies and improved treatment decision-making, paving the way for more personalized and effective healthcare solutions.[17]

GENETIC VARIATIONS AND THEIR INFLUENCE ON HEALTH

Genetic variations are key factors in shaping an individual's health, influencing everything from disease susceptibility to treatment response.[18] These variations occur in different forms, including single nucleotide polymorphisms (SNPs), mutations, and structural variations such as insertions, deletions, and copy number variations (CNVs). Each of these can impact biological processes and contribute to an individual's overall health profile.[19]

SNPs are the most common type of genetic variation, involving a change in a single base pair of the DNA sequence, make up around 90% of genetic differences between individuals.[20] While many SNPs are harmless, some can have significant effects on gene function or expression, thereby affecting disease risk or drug metabolism.[21] For example, SNPs in the BRCA1 and BRCA2 genes are known to greatly increase the risk of developing breast and ovarian cancers.[22]

Mutations, on the other hand, refer to changes in the DNA sequence that can either be inherited or acquired during a person's lifetime.[23] Some mutations may be benign, while others can result in serious health conditions, including cancer or inherited genetic disorders.[24] A well-known example is mutations in the TP53 gene, which are 50% found in cancer and play a role in promoting uncontrolled cell growth.[25]

Finally, structural variations like CNVs, where sections of the genome are duplicated or deleted, can have a significant impact on health. These larger-scale variations are often linked to complex conditions such as neurodevelopmental disorders.[26] Structural variations like CNVs affect 10% of the genome and are linked to conditions like autism, where some CNVs increase risk by up to 10-fold. For instance, certain CNVs have been associated with an increased risk of autism and schizophrenia, highlighting the profound effects that these genetic alterations can have on development and health.[27]

KEY TECHNOLOGIES ENABLING PERSONALIZED MEDICINE

Several advanced technologies have been fundamental in advancing personalized medicine, enabling scientists and

clinicians to decode and manipulate the human genome with remarkable precision.[28]

WGS offers a comprehensive analysis of an individual's entire genetic blueprint, allowing for the identification of genetic variants that may affect health or treatment responses.[29] This technology provides a broader scope than targeted methods, such as exome sequencing, and is especially useful for uncovering rare genetic mutations that could remain undetected with more focused approaches.[30] WGS has proven invaluable in diagnosing rare diseases, pinpointing cancer-related mutations, and informing personalized treatment strategies.[29] For example, it is being used to identify mutations in pediatric patients with unexplained developmental delays, enabling more targeted interventions.

The emergence of CRISPR-Cas9 has revolutionized genetic editing, allowing for precise modifications to DNA.[31] CRISPR acts as a molecular "scissors," enabling the correction of disease-causing mutations and the enhancement of beneficial traits. Although clinical applications are still in early development, CRISPR shows great promise in treating genetic disorders by directly targeting their underlying genetic causes.[32] Current research is exploring its potential in correcting mutations associated with conditions such as sickle cell anemia and cystic fibrosis.[33] Similarly, trials are exploring CRISPR's potential to target genes associated with inherited blindness and certain cancers, demonstrating its versatility.[34]

Genome-wide Association Studies (GWAS) involve scanning the genomes of large populations to identify genetic variants that are linked to particular diseases or traits.[35] GWAS has been instrumental in identifying genetic risk factors for complex diseases such as diabetes, cardiovascular conditions, and Alzheimer's disease.[36] By detecting SNPs and other genetic variations associated with disease susceptibility, GWAS plays a critical role in developing new diagnostic tools and therapeutic approaches.

The integration of these technologies into clinical practice is further supported by advancements in bioinformatics and machine learning.[37] Figure 1 indicate the various integration of diagnostics and integrations. These tools allow for the efficient analysis and interpretation of large-scale genetic datasets, ultimately helping healthcare providers to apply genetic insights in clinical settings.[38] The combination of WGS, CRISPR-Cas9, GWAS, and computational tools is propelling personalized medicine toward realizing its full potential in precision healthcare.

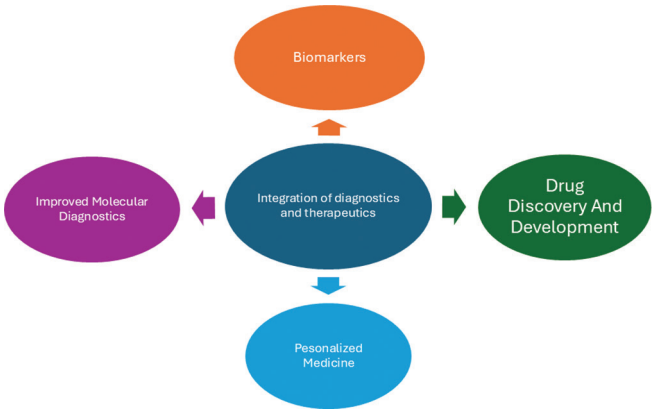

Figure 1: Role of biomarkers in personalized medicine

GENETICS GUIDES TO THE DEVELOPMENT OF INDIVIDUALIZED TREATMENT PLANS

The fundamental principle of personalized medicine is the customization of treatment based on the unique characteristics of each patient, rather than relying on one-size-fits-all approaches.[11] Genetics is central to this customization, offering crucial insights that guide the development of individualized treatment plans. Genetic testing reveals how a person's genetic makeup affects their risk for certain diseases, their response to therapies, and the likelihood of ADRs.[39]

In oncology, tumor genetic profiling is widely used to identify mutations that drive cancer progression. By examining the specific genetic alterations within a tumor, oncologists can select targeted therapies that inhibit the pathways activated by these mutations.[24] For instance, in patients with non-small cell lung cancer who have mutations in the EGFR gene, therapies like tyrosine kinase inhibitors are prescribed to block the abnormal signaling pathways involved in cancer growth. This approach not only enhances treatment efficacy but also reduces side effects, as therapy is tailored to the patient's tumor biology.[40]

In the field of pharmacology, pharmacogenomics plays a crucial role in individualizing drug therapies. This field studies how genetic variations, particularly in genes such as CYP2C9 and CYP2D6, influence drug metabolism and efficacy. For instance, genetic variants in these genes can impact how patients metabolize drugs such as warfarin, antidepressants, or opioids. By testing for these variations, clinicians can adjust drug dosages or select alternative treatments, thereby improving therapeutic outcomes while minimizing adverse effects.[41]

Similarly, in cardiovascular medicine, genetic testing has influenced the development of targeted treatments.[42] For example, mutations in the PCSK9 gene, which are associated with high cholesterol levels in familial hypercholesterolemia, have led to the development of PCSK9 inhibitors. These drugs effectively lower cholesterol levels in individuals with these genetic mutations, exemplifying how genetics not only informs the choice of existing treatments but also drives the innovation of new therapies for previously difficult-to-treat conditions.[43]

THE ROLE OF GENETICS IN DRUG RESPONSE

The human genome, the complete set of genetic instructions for building and maintaining an organism, varies significantly among individuals. These genetic variations, or polymorphisms, can profoundly influence how the body processes and responds to drugs.[44] Since each person's genetic makeup is unique, even minor differences in DNA sequences can cause considerable differences in how drugs are absorbed, processed, and eliminated from the body. One of the most common forms of genetic variation is SNPs, which can affect the function of enzymes, drug transporters, and receptors involved in drug metabolism. These variations play a key role in shaping individual drug responses, influencing both the effectiveness and potential side effects of treatments.[45]

Among the various aspects influenced by genetic variations, the most common is the effect on cytochrome P450 enzymes, usually referred to as CYP enzymes, which are those that metabolize most of the drugs used in clinical practices. For example, some people may possess genetically determined mutations of the enzymes that lead to slow metabolism or high metabolism of drugs.[46] Substantial evidence is available and it has indicated that poor metabolizer phenotypes may suffer from a poor drug metabolic enzyme hence accumulating the drugs in their body, leading to high risks of developing toxicity or ADRs.[47] On the other hand, ultra-rapid metabolizers can process drug from their body systems very fast and hence the effectiveness may greatly be minimized.[48] One well-understood example is the CYP2D6 enzyme, which plays a role in the metabolism of a wide range of drugs that include tricyclic antidepressants, opioids, and beta-blockers. Different alleles of the CYP2D6 gene give rise to poor metabolizers, intermediate metabolizers, extensive metabolizers, and ultra-rapid metabolizers which decide the likelihood of how successfully patients respond to drugs which are metabolized by this enzyme.[49]

PHARMACOGENOMICS: IDENTIFYING GENETIC MARKERS ASSOCIATED WITH DRUG RESPONSE

Pharmacogenomics is the application of genomic information to improve drug metabolism, calling for the examination of genetic factors in response to drugs.[54] Based on studying the genetics of people, it is possible to find out certain genes that serve as some kind of indicators of the various metabolism or efficiency of certain drugs.[55] It is therefore possible to determine in advance how a particular patient will be likely to respond to a given drug. Pharmacogenomic testing usually involves determining the presence of certain genetic biomarkers in a patient's genome.[56] This may be accomplished employing methods such as the genotyping arrays together with WGS. Once the patient's genotype is established, then it can be matched with other known genetic profile that is associated with the reaction to a particular drug [Table 1]. Relative to guideline development, the Clinical Pharmacogenetics Implementation Consortium has been instrumental in integrating pharmacogenomic research findings into practice by creating the first set of recommendations for clinicians on how to use genetic test information to guide drug selections.[57] These are drawn out from genetic variants that are known to have an impact on drug metabolism and thus assist the clinicians to prescribe medicines according to the patient.[58]

CLINICALLY RELEVANT PHARMACOGENETIC BIOMARKERS

Several pharmacogenetic biomarkers are currently used in clinical practice to guide drug therapy decisions. Some of the most clinically relevant examples include [Table 2]:

Pharmacogenomic testing helps optimize drug therapy by identifying genetic markers that impact drug metabolism and response. For instance, genetic testing for CYP2C9 and VKORC1 variants in patients taking warfarin can reduce adverse bleeding risks by up to 50%. Similarly, TPMT testing in patients undergoing treatment with thiopurines reduces the risk of severe bone marrow toxicity by 30–40%. Moreover, the cost of pharmacogenomic testing typically ranges from $300 to $1,000, but it offers substantial long-term savings by reducing hospital admissions and improving treatment efficacy. Clinical case studies show that pharmacogenomic-guided treatment can improve drug efficacy and reduce adverse reactions by 60–70%, as demonstrated in warfarin dosing and EGFR-targeted therapy for lung cancer, which has been associated with a 50% improvement in survival rates. These data underscore the clinical and economic benefits of incorporating genetic testing into drug prescribing, leading to more personalized and effective treatments.

ETHICAL CONSIDERATIONS AND CHALLENGES

Personalized medicine raises several ethical concerns, with privacy being a primary issue. The vast amount of genetic data collected for personalized treatments poses significant risks if improperly handled or breached. Ensuring the confidentiality of genetic information is critical, as unauthorized access could lead to misuse by third parties, such as employers or insurance companies. This brings up the concern of genetic discrimination, where individuals may be treated unfairly based on their genetic predispositions.[64] The Genetic Information Non-discrimination Act (GINA) in the U.S. offers some protection against this, but similar protections are not universally available, leaving gaps in

Table 1: Genotyping arrays versus whole-genome sequencing in clinical applications

Aspect	Genotyping arrays	Whole-genome sequencing
Cost	$50–$200 per sample (more affordable)	$500–$1,000 per sample (more expensive)
Accuracy	Limited to predefined variants (single nucleotide polymorphisms, etc.)	Comprehensive, covers entire genome, including coding and non-coding regions
Scope	Focuses on specific known genetic variants	Provides a complete genetic blueprint, including rare mutations and structural variants
Clinical Applicability	Suitable for population-level studies, pharmacogenomics, and risk assessments	Ideal for diagnosing rare diseases, identifying cancer-related mutations, and personalized treatments
Use in Personalized Medicine	Used for risk prediction and drug response (e.g., pharmacogenomics)	Crucial for rare disease diagnostics, cancer genomics, and custom treatment plans
Limitations	Cannot detect novel or rare mutations, restricted to known variants	Higher cost and resource-intensive; may not be necessary for all clinical cases
Current Examples	Used in large-scale studies like Genome-Wide Association Studies, pharmacogenomic testing	Used in personalized cancer therapies, rare disease diagnosis, and genetic counseling
References	[50,51]	[52,53]

Table 2: Different biomarker with its genetic variant and its clinical significance

Biomarker	Drug	Condition	Genetic variant	Clinical significance
CYP2C9 and VKORC1	Warfarin	Anticoagulation (prevent blood clots)	CYP2C9 and VKORC1 variants	Genetic variations in CYP2C9 affect warfarin metabolism, and VKORC1 variants alter sensitivity. Testing enables precise dosing, reducing bleeding/ clotting risk.[59]
CYP2D6	Codeine	Pain relief	CYP2D6 variants	Ultra-rapid metabolizers risk morphine toxicity, while poor metabolizers experience ineffective pain relief. Testing guides alternative pain management.[60]
HLA-B*57:01	Abacavir	HIV Treatment	HLA-B*57:01 allele	Patients with HLA-B*57:01 allele is at high risk for severe hypersensitivity. Testing ensures safe use of abacavir by identifying those at risk.[61]
TPMT	Thiopurines (e.g., azathioprine, mercaptopurine)	Cancer, Autoimmune Diseases	TPMT variants	Reduced TPMT enzyme activity increases the risk of severe bone marrow toxicity. Testing allows dose adjustments to avoid life-threatening toxicity.[62]
SLCO1B1	Statins	Hypercholesterolemia	SLCO1B1 variants	Variants increase the risk of statins-associated myopathy. Testing helps adjust statin dosing or switch to alternative therapies to avoid muscle complications.[63]

safeguarding against discrimination. Equity is another major ethical concern. Access to personalized medicine, including genetic testing and tailored treatments, is often limited by socioeconomic factors.[65] Wealthier individuals may have better access to advanced treatments, while lower-income or underserved populations may be excluded, widening healthcare disparities. This inequity also extends to the data itself, as current genomic research often over-represents populations of European descent, limiting the generalizability of personalized medicine to other racial and ethnic groups. Informed consent is a cornerstone of ethical medical practice, but it becomes more complex in the context of personalized medicine. Patients must fully understand what their genetic information will be used for, the risks involved, and potential long-term implications. The complexity of genomic data makes it difficult for patients to fully grasp how their genetic material might be analyzed and interpreted. This creates challenges in ensuring patient autonomy, as individuals may agree to procedures without fully understanding the potential consequences, such as the discovery of incidental findings or risks of future health conditions. Another ethical concern is the potential for genetic testing to exacerbate existing health disparities. As personalized medicine relies heavily on genetic data, underserved populations, who are

often underrepresented in genetic research, may not benefit equally from advancements. The limited diversity in genetic studies may lead to less effective or inaccurate treatments for minority groups, perpetuating inequalities in healthcare. To tackle ethical concerns in personalized medicine, we can focus on creating stronger privacy protections for genetic data, expanding laws like GINA globally to prevent discrimination, and making genetic testing and treatments more affordable to reduce disparities. Efforts should also include diversifying genetic research to include underrepresented groups and ensuring patients fully understand the implications of genetic tests through clearer communication and education for both patients and healthcare providers. These steps will build trust and make personalized medicine accessible and fair for everyone. Addressing this requires more inclusive research efforts to ensure that the benefits of personalized medicine reach all populations, not just those who are already well-represented in genomic databases.

FUTURE DIRECTIONS AND OPPORTUNITIES

The future of personalized medicine is closely linked to emerging technologies and continued research in genomics, artificial intelligence (AI), and bioinformatics. AI and machine learning are playing increasingly vital roles in analyzing complex genetic data, identifying patterns, and predicting outcomes more accurately.[66] Gene editing technologies, such as CRISPR-Cas9, present opportunities to not only tailor treatments but also correct genetic mutations, potentially curing hereditary diseases. In addition, advancements in biomarker discovery and multi-omics approaches (such as proteomics, transcriptomics, and metabolomics) will enhance our understanding of disease mechanisms, enabling more precise interventions.[67]

To realize the full potential of personalized medicine, collaboration between researchers, clinicians, and policymakers is crucial. Researchers must work closely with clinicians to translate laboratory findings into practical treatments, while policymakers need to create frameworks that facilitate the integration of personalized medicine into healthcare systems.[68]

These collaborations can also help establish regulatory guidelines that ensure patient safety, promote equitable access, and address ethical concerns related to genetic data use. Several strategies can be implemented to overcome the challenges associated with personalized medicine. First, expanding diversity in genomic research is essential to ensure that personalized treatments are effective across all populations.[69] This includes initiatives to include underrepresented groups in genetic studies and the development of more inclusive biobanks. Second, creating affordable genetic testing and therapies can help mitigate the issue of healthcare inequality. Policymakers and healthcare organizations must work together to reduce the costs of these advanced treatments through subsidies, insurance coverage, or public-private partnerships.[70] In addition, developing comprehensive privacy laws and protections against genetic discrimination will help safeguard individuals' rights and build public trust in personalized medicine. Finally, educational initiatives to improve clinicians' understanding of genomics and pharmacogenomics are crucial for successful integration into clinical practice.[15]

CONCLUSION

This review highlights the vast potential of personalized medicine to improve patient outcomes and transform healthcare. By leveraging genetic and molecular information, personalized medicine offers the opportunity for more targeted and effective treatments, reducing the risks of ADRs and improving disease prevention and management. However, significant challenges remain, including high costs, ethical concerns, privacy issues, and the potential to exacerbate healthcare disparities. By addressing these challenges and fostering innovation, personalized medicine has the potential to revolutionize healthcare, making treatments more precise, effective, and accessible for all patients.

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