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Personalized Medicine and Pharmacogenomics: A Comprehensive Review

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Abstract:

Pharmacogenomics enables the development of tailored therapy for individual patients. Momentous advances in DNA sequencing and genotyping have accelerated the discovery of single-nucleotide polymorphisms and mutations that influence drug metabolism, transport, and targets. Multi-analyte arrays have been developed to simultaneously assess genetic variants, aiding in the treatment of oncology and cardiology conditions. These advances are driving the implementation of pharmacogenomics in actual clinical settings and ushering in a paradigm shift toward individualized medicine.

INTRODUCTION

Personalized medicine represents a novel healthcare approach that embodies the concept of tailoring medication to individual patients (de Leon, 2009). The realization of such customized therapies is underpinned by advancements in genomic research, leading to the emergence of pharmacogenomics over the past decade (Lam, 2013). Pharmacogenomics elucidates the contribution of genes to interpatient variability in drug response and seeks to guide optimal drug prescription accordingly (Giannopoulou *et al.*, 2019). It represents a burgeoning area of research and debate, with ongoing efforts directed towards harnessing this discipline to realize personalized medicine in clinical practice (Tripathi *et al.*, 2025).

Historical Background of Personalized Medicine

Development of combined clinical and genetic models improved genotype discrimination and age of onset prediction for those at elevated risk (Dite *et al.*, 2021). The predictive value of such combined tests depends on the strength of clinical and genetic risk factors; strong genetic risk factors can guide targeted preventive interventions (de Leon, 2009).

Variation in clinical response to therapeutic dosage was reported in the 1950s, soon followed by the identification of monogenic polymorphisms associated with drug metabolism, transport, or targets (Vippamakula *et al.*, 2024). Pharmacogenomic-guided therapy relies on the premise that much pharmacokinetic and pharmacodynamic variability is genetically determined (Diasio *et al.*, 2021). Fully personalized-dose therapy remains futuristic, but pharmacogenomics aims to maximize efficacy and minimize toxicity (Lam, 2013).

Personalized medicine—or precision medicine—is a form of healthcare delivery that considers patient-specific information, including genes, proteins, environment, and lifestyle (Taherdoost and Ghofrani, 2024). Recent advances in pharmacogenomics (PGx) have markedly enhanced the ability to predict patients' drug response profiles (Pirmohamed, 2023). These improvements enable identification of drug and dosage regimens less prone to adverse reactions and failures, leading to more effective and safer pharmaceuticals (Carr *et al.*, 2014).

Understanding Pharmacogenomics

In the quest for more effective treatment and dosage, considerable attention has been focused on the role of genetics (Iqbal and Ashraf, 2025; Iqbal *et al.*, 2021a; Stanley, 2024). Advances in gene sequencing, computational analysis, and genomics have enabled researchers to identify thousands of variations in the genes involved in drug metabolism, transport, and targets (Lam, 2013). Using the information, it has become possible to predict whether a patient will metabolize a particular drug rapidly, slowly, or at an intermediate rate (Zhao *et al.*, 2021). By better understanding mechanisms of intrinsic or acquired drug resistance due to genetic polymorphisms, new drugs can be designed to more effectively target pathways associated with particular genetic variations, avoid mechanisms that lead to drug resistance, and improve efficacy (Iqbal *et al.*, 2021b; Suzuki *et al.*, 2023).

Pharmacogenomics studies the role of the genome in drug response (Papachristos *et al.*, 2023). The term is interchangeable with pharmacogenetics but is sometimes used more broadly to refer to the use of genomic technologies such as single-nucleotide polymorphism (SNP) genotyping, RNA expression analysis, and whole-genome association studies to elucidate the genetic basis of drug response (Qahwaji *et al.*, 2024). Pharmacogenomics aims to develop rational means to optimise drug therapy, with respect to the patients' genotype, to ensure maximum efficacy with minimal adverse effects (Paswan *et al.*, 2025). Studies of the human leukocyte antigen (HLA) genes, which have wide polymorphisms of extensive immunogenic specificity, have also provided important insight into a priori "prognostic" indicators that can be identified without respect to the nature of the drug being administered (Vemula *et al.*, 2023). Better understanding of gene-drug interactions

should make it possible to apply genomic technologies routinely in the quest for a more personalized approach to medicine (Ferreira *et al.*, 2025).

The Role of Genetics in Drug Response

One of the fundamental challenges in pharmacogenomics is to understand how genetic variation impacts the pharmacokinetics and pharmacodynamics of drugs (Brunet and Pastor-Anglada, 2022). Although traditional laboratory and animal studies have yielded a great deal of information regarding drug metabolism and the effects of drugs in normal individuals, population studies often demonstrate wide variation in these processes (Soria-Chacartegui *et al.*, 2021). Such variability in clinical response to a standard therapeutic dosage of a drug was first reported in the 1950s (Hahn and Roll, 2021). It has subsequently been demonstrated that monogenic polymorphisms are associated with marked differences in drug metabolism, transport, or drug targets (Ji *et al.*, 2021). These observations provided the initial impetus for the development of a personalised approach to drug therapy (Langmia *et al.*, 2021). In addition, it is recognised that nongenetic factors, such as age, gender, body mass, and alterations in organ function, also contribute to clinical variability (Tsunoda *et al.*, 2021). Because it has become increasingly apparent that much of the interindividual variability in drug response is genetically determined, pharmacogenomics offers a scientific foundation that not only rationalises variable drug activity but also provides a series of testable hypotheses (Qahwaji *et al.*, 2024).

Advancements in Genomic Technologies

Next-generation sequencing (NGS) enables rapid, cost-effective sequencing of entire human genomes and can be combined with complementary technologies to derive a diverse range of additional information (Tafazoli *et al.*, 2021). Despite ongoing challenges, such as inaccuracies in some forms of structural variant detection, NGS provides a widely applicable platform for comprehensive pharmacogenomic analysis (Wang *et al.*, 2025).

Clinical Applications of Pharmacogenomics

Healthcare is moving toward a patient-centric model that emphasizes tailored care, patient involvement in healthcare decisions, and collaborative partnerships to maximize improved well-being (Balogun *et al.*, 2024). The paradigm shift from a reactive “one-size-fits-all” model to a proactive, predictive, individualized, and participatory approach is starting to address many challenges and opportunities in a continually evolving healthcare ecosystem (Lam, 2013).

To achieve the new model, all components that affect health and well-being need to be revisited and potentially revised, including medication use (Pirmohamed, 2023). The use of pharmacogenomics, the study of how an individual’s genetics influences drug response, allows healthcare professionals to select an agent more precisely with reduced possibility of toxicity (Olagunju, 2023). The intrinsic variability of an individual’s response to a given drug dosage has been recognized and reported since the late nineteenth century (Guy *et al.*, 2020). Pharmacogenomics is becoming an integral part of both the discovery and clinical evaluation of new drugs, with the ultimate goal of making personalized medicine available for many diseases (Carter *et al.*, 2022).

Patient-Centric Models in Healthcare

Healthcare models emphasizing patient needs, preferences, and tailored care are a natural extension of personalized medicine to the clinical encounter (Burnette *et al.*, 2012). Personalized medicine fosters such models through both a foundation of supporting evidence and a framework for practical clinical use (Godman *et al.*, 2013). The principles of personalized medicine anticipate and encourage the adoption of patient-centric structures in parallel with rapid advances in genetic knowledge, the maturation of supporting technologies, and the arrival of practical applications (Cinti *et al.*, 2024).

Integrating Pharmacogenomics into Clinical Practice

Efforts to implement pharmacogenomics—understood from a healthcare perspective as the tailoring of drug therapy based on an individual's genome—face a broad array of scientific and human barriers. Such barriers can be examined at several stages of development and implementation, when a healthcare system contemplates adoption of a pharmacogenomic application (Lam, 2013).

In considering adoption, a system can look to evidence of clinical value and relevant regulatory information prior to deciding whether to deploy a test or spend the resources needed for inclusion in a clinical decision-support system (Costa *et al.*, 2025). When ready to introduce a test, available clinical guidelines are important, and acceptance by physicians often depends on the familiarity of the recommended usage (Baumfeld Andre *et al.*, 2022). Following implementation, performance must be reviewed and tested continuously to evaluate whether the test provides sufficient benefit—then many details follow, including how positive test results impact drug choice and regimen, ease of test generation, and required laboratory resources (Mahendraratnam *et al.*, 2022). Time to turnaround for the test is important, although interim measures, such as providing alternative drugs, can be used while results are pending (Dang, 2023). Throughout all phases of implementation, a wide variety of human factors determine success or failure (Alexander *et al.*, 2021). Scientific methods for weighing evidence and calculating impact remain immature (Vasey *et al.*, 2022).

Role of Pharmacists in Personalized Medicine

Personalized medicine helps select what medication and dose will work best for each patient based on their genes, environment, and lifestyle (Naithani *et al.*, 2021). Pharmacogenomics—the study of how genes affect drug response—enables more precise, evidence-based treatments (Wang and Wang, 2023).

Pharmacists play a vital role. They review patients' responses, check for drug interactions to prevent life-threatening reactions, and adjust doses based on genetic test results (Alanazi *et al.*, 2024). They share expertise with healthcare teams to select the most effective therapies and recognize adverse responses (Kumar, 2024). This collaborative approach ensures that patients receive prescriptions best tailored to their needs, preferences, and histories (de Leon, 2009). Pharmacists complement clinicians skills by offering scientific insights that enhance personalized care (Giannopoulou *et al.*, 2019).

Global Perspectives on Personalized Medicine

FDA regulatory perspectives are available in the FDA guidance on pharmacogenomics, developing approaches to integrate pharmacogenomic data in regulatory evaluation of medical products (Khoury *et al.*, 2025). In the USA, personalized medicine in hematology/oncology is increasingly implemented in clinical practice, and in 2007, nearly 70% of patients waited four weeks or longer to access targeted personalized medicines under clinical development protocols, affecting uptake (Wästerlid *et al.*, 2022). Concerns about costs have emerged for adopting personalized medicine worldwide, while the NIH Pharmacogenetics Research Network launched initiatives to develop new assay technologies, enroll patients in genotyping studies, and advance clinical interventions (Godman *et al.*, 2013).

Personalized Medicine in Oncology

Oncology represents a leading application area for the preemptive prediction of drug response and toxicity, offering a wealth of molecular biomarkers—genomic, epigenomic, and others—that can inform treatment selection and monitoring (Lauschke *et al.*, 2019). Tailoring treatment to an individual's genetic makeup can reduce therapeutic failure and the incidence of severe, potentially life-threatening side effects (Partin *et al.*, 2023). Most anticancer drugs exhibit narrow therapeutic windows and considerable pharmacokinetic and

pharmacodynamic variability; consequently, a standard regimen embraces the considerable risk that a patient will either not respond or be exposed to excessive toxicity (Baptista *et al.*, 2021).

Pharmacogenomics investigates how genetic variations affect drug disposition and action, focusing on the consequences of interactions with specific proteins such as drug transporters, enzymes, and targets (Li and Bluth, 2011). These determinants regulate not only absorption, distribution, metabolism, and elimination but also the extent of target engagement and the magnitude of secondary effects (Cacabelos *et al.*, 2021). The existing evidence indicates that genetic variation in drug-metabolizing enzymes, transporters, and targets can influence both the pharmacological efficacy and the toxicity of chemotherapeutic agents, which is particularly relevant to oncology (Ahmed *et al.*, 2016). The discovery of somatic mutations in pharmacodynamic genes enables the use of drugs such as epidermal growth factor receptor inhibitors, BRAF inhibitors, and ERBB2 targeting agents in a targeted, peri-therapeutic fashion (Dash *et al.*, 2024). Whole-genome sequencing of the somatic cancer genome is increasingly employed to personalize treatment beyond a few common mutations (Vippamakula *et al.*, 2024).

Role of Artificial Intelligence in Personalized Medicine

Artificial intelligence (AI) technologies facilitate the analysis of medical data and the decision-making process in personalized medicine (Ahmed, 2020). Multi-omics (genomics, transcriptomics, and proteomics) data and clinical data analysis represent a challenge in developing data-driven therapeutic interventions for personalized medicine (Perlekar and Desai, 2025). AI has proven to be a key enabling technology, supporting the categorization of interaction patterns among variables, learning from previous experiences, and predicting better orientations (Johnson *et al.*, 2021). Based on medical history, AI models could predict the existence of the risk for a life-threatening disease at an early stage of disease development (Chakravarty *et al.*, 2021).

Furthermore, AI frameworks improve the identification of the most relevant variables for patient data stratification prior to assessing the outcomes of the applied treatments (Li *et al.*, 2024). The application of AI in clinical data analysis enhances the investigations of existing or hidden correlations among available clinical information (Boniolo *et al.*, 2021). AI also supports the assessment of genotype and phenotype association among diseases (Mahabub *et al.*, 2024). To understand how particular genetic variants contribute to the health state of each individual, AI explores the protein, metabolic, and biochemical pathways (Liao *et al.*, 2023). AI tools can profile a personal metabolome, find metabolite penetrance within a patient population, and analyze the metabolic pathways by associating multimodal data (Vadapalli *et al.*, 2022). In precision medicine, the analysis starts with the individual genome, followed by multimodal omics data and the available clinical and hospital data (Taimoor and Rehman, 2021). AI accelerates the discovery of associations, underpins the clustered streamline fitting between the heterogeneous data sources, and facilitates the formulation of hypotheses for potential clinical issues (Marques *et al.*, 2024).

Impact of Personalized Medicine on Drug Development

Drug development and approval may be impacted by numerous changes across the pharmaceutical industry stemming from the application of personalized medicine approaches (Marques *et al.*, 2024). Drug characteristics will need to be reconsidered throughout the pipeline, including target selection, screening, lead optimization, candidate selection, clinical trial design, regulatory approval, and marketing (Wang and Wang, 2023). The pharmaceutical industry adopts individualized medicine technologies to improve efficiency and create money-saving, better drugs (Fountzilas et al., 2022).

Variability in clinical response to standard therapeutic dosage was reported during the

1950s, eventually leading to the realization of associations between common monogenic polymorphisms and inter-individual variations in drug metabolism, transport, or targets (Diasio *et al.*, 2021). Pharmacogenomic-guided drug therapy is based on the premise that much of the observed variability in drug response between patients is genetically determined (Vippamakula *et al.*, 2024). Despite scientific and clinical advances, personalised therapy tailored to an individual's genetic profile remains a goal yet to be fully realized (Xu *et al.*, 2024). Pharmacogenomic tests have to pass through several developmental stages (biomarker discovery and validation, replication of association, demonstration of clinical utility, regulatory approval, and clinical implementation) (Ingelman - Sundberg and Molden, 2025). Challenges and barriers remain at each stage of development, involving different groups of stakeholders with diverging agendas (Zhang *et al.*, 2025). Integrating pharmacogenetics in the drug development process can potentially help to overcome the above challenges (Jethwa *et al.*, 2025).

The concept of "individualized medicine", which refers to the tailoring of medical treatment to the individual characteristics of each patient, is being reconsidered in parallel with the recent progress in pharmacogenomics that enables the classification of patients into responders or a variety of non-responders to specific treatments (Kumar, 2024). Personalized medicine represents a fast-growing field aiming to use knowledge about the underlying genetic and molecular mechanisms of the patient's disease in order to select an efficient medication at an early stage (Li and Bluth, 2011).

CONCLUSION

Despite their promise, pharmacogenomics and personalized medicine remain unfamiliar and underutilized. Effective translation must overcome barriers: redirecting drug development toward tailored therapies; accommodating smaller sub-populations in clinical trials; assuaging health authority and insurance concerns; and enhancing education and training. Advancing clinical interpretation of genetic test results also requires a greater understanding of pharmacogenomic variation, including the functional impact of non-coding elements, in concert with complementary factors that influence drug response, such as pharmaceutical formulations, disease, age, and environmental variables. The effort should produce measurable improvements in patient care and provide a foundation for personalized drug development and reimbursement. A positive outlook remains: the accumulated knowledge on pharmacological interactions, personal variables, genetic tests, and therapeutic drug monitoring can already support personalized dosing regimens for some drugs, especially those with narrow therapeutic windows. However, appropriate expertise, for example, in psychiatry, is essential for realizing the full benefits of personalized prescription based on pharmacogenomics.

CONFLICT OF INTEREST

Author hereby declares no conflict of interest.

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