Integrating Pharmacogenomics into Clinical and Microbial Practice: A Pathway for Personalized Healthcare

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Abstracts

Pharmacogenomics, the science of studying how genetic variation affects drug response, provides the backbone for personalized medicine. It improves therapeutic outcomes, reduces ADRs, and tailors drugs to individual patients by integrating genetics with pharmacology. This paper discusses the application of pharmacogenomics in clinical and microbial settings and indicates the prospect of it revolutionizing health care through personalized treatment approaches. Pharmacogenomics has been touted to help improve drug safety, at least in fields like oncology, psychiatry, and infectious diseases, all of which make use of genetic biomarkers in medicine choice and dosing. Many challenges have marred widespread adoption, among them lacking provider education, high test costs, ethical issues, and unequal access. It shall analyze some of the gaps that this paper seeks to close concerning clinical decision support systems and guidelines, including those that the Clinical Pharmacogenetics Implementation Consortium has proposed. Further, it shall cover the application of pharmacogenomics in fighting antimicrobial resistance and how it may benefit therapy development. As healthcare shifts toward precision medicine, pharmacogenomics might become transformative, but that success will depend on the reduction of barriers through education, research, and policy changes.

Keywords: Pharmacogenomics; Pharmacogenomic biomarkers; Personalized medicine; antimicrobial resistance; Clinical Pharmacogenetics.

1. Introduction

Pharmacogenomics is part of personalized medicine and relates to how genetic information affects the way a patient reacts to drugs. This study combines pharmacology and genomics to understand the association between genetic difference and drug efficacy or toxicity in order to aim finally at personalizing drug treatment according to the patient's genetic makeup (Lee et al., 2023; Zhang et al., 2015). The importance of pharmacogenomics in modern healthcare is profound because it has the potential to improve the outcome of therapy, minimize adverse drug reactions (ADRs), and optimize drug dosing strategies.

The most important advantage of pharmacogenomics is its ability to reduce the incidence of ADRs, which is a significant cause of morbidity and healthcare costs. About one-quarter of all outpatients receive medications affected by pharmacogenomic factors, especially in the treatment of cancer where drug-gene interactions play a significant role (Patel, 2016; Mahmutović et al., 2018). For instance, the existence of specific genetic markers can determine which anticancer drugs to give patients so they receive the best possible treatment with the fewest adverse effects (Wheeler et al., 2012; Brown et al., 2018). In addition, the results of pharmacogenomic testing can lead to more informative practice for prescribing because clinicians might use genetic information for the prediction of drug response in patients, thus implying safer and more effective therapy regimens (Crews et al., 2012; Caudle et al., 2014).

However, clinical practice has its challenges when pharmacogenomics is applied in clinical areas; there are education-related difficulties with professional health providers and good clinical guidelines to base decisions on. Most clinicians believe that they are inadequately educated to assume that they can express confidence over the knowledge they have with respect to pharmacogenomics; this is a problem that deters the acceptance of genetic testing into general practice (Abdela et al., 2017; Soo et al., 2023; McCullough et al., 2011). It calls for education among current providers and students in the health sector to fill in the gap and make pharmacogenomics part of the understanding about patient care (Moen & Lamba, 2012; Just et al., 2017). In addition, it develops comprehensive guidelines, such as those developed and provided by the Clinical Pharmacogenetics Implementation Consortium (CPIC), in guiding the translation of pharmacogenomic data into actionable decisions in the clinic (Caudle et al., 2014; Yoon et al., 2020).

Lastly, pharmacogenomics is increasingly recognized as a means to drive the advancement towards precision medicine. Pharmacogenomics improves patient outcomes for each individual while at the same time contributing to the public health initiatives by identifying population-specific health disparities for it allows healthcare providers the ability to tailor treatments in accordance with genetic profiles (Stankovic et al., 2020; Ranade, 2022). The fact that the ongoing studies and the mounting evidence point out how genetic factors play a significant role in drug response supports the shift from a single size fits all to a personalized strategy in drug therapy (Sangeeta, 2019; Vojvodic et al., 2021). The main goals for implementing pharmacogenomics in personalized health care include tailoring the treatment with drugs to fit an individual's genetic profile in order to maximize treatment outcomes and minimize adverse drug reactions. Pharmacogenomics also focuses on making the basis of medical treatment more

characteristic to a patient; that is, a shift from the traditional one-size-fits-all approach in medicine (Sangeeta et al., 2019)

The main goal is to have improved safety and efficacy for drug therapies and, indeed, pharmacogenomics allows this. Which means to know the variations in a person's drug metabolism due to genetic mutations and variations so that proper medication, dosage, etc., will be chosen to be made by the practitioner (Micaglio et al., 2021). For instance, pharmacogenomic testing may detect patients who are prone to severe side effects due to specific medications, enabling clinicians to select alternative therapies or adjust dosages for these patients (Rahma et al., 2021). This is very important in vulnerable populations such as pediatric and elderly patients, where the risk of ADRs is much higher (Micaglio et al., 2021).

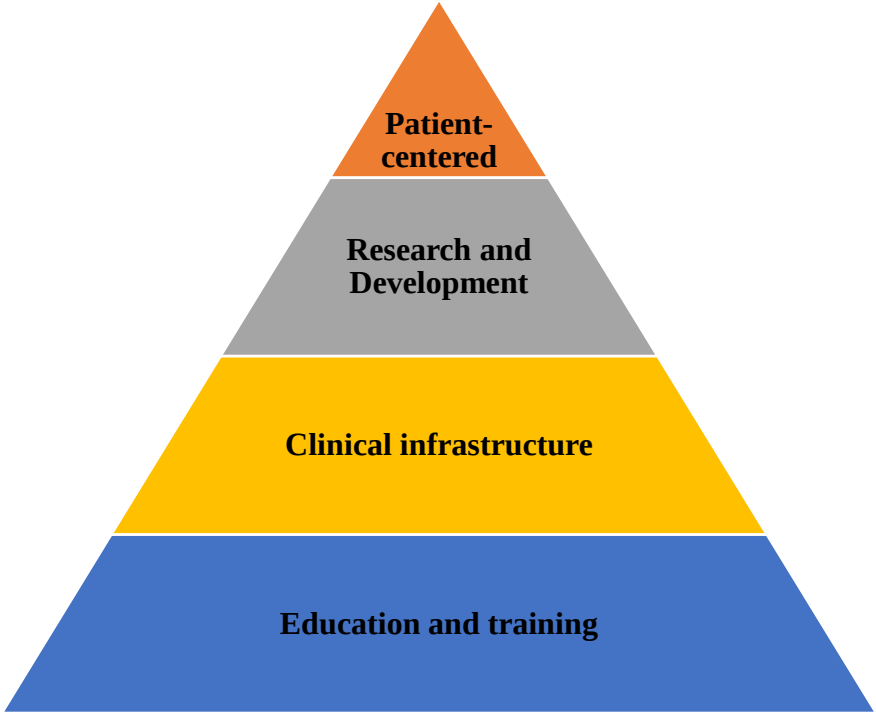

Figure 1. Pillars of Pharmacogenomic Success

Another critical goal is the creation of new drugs that will be designed for specific genetic backgrounds. This may happen through repositioning currently existing medications for new clinical indications based on genetic insights, which can be particularly helpful for treating rare diseases (Micaglio et al., 2021). As pharmacogenomic information increases, it is expected that combining genomic data with other -omics profiles, including the epigenome and microbiome, will add another layer of detail to the precision of personalized medicine (Wouden et al., 2020).

In addition, pharmacogenomics aims at educating healthcare professionals and integrating this information into practice. There is a recognized need for increased education in pharmacogenomics among those students of medicine and pharmacy, as well as practicing clinicians who would assist them to be adequately prepared to interpret the results from pharmacogenomic tests and apply them subsequently in patient care (Pisanu et al., 2014; Moen & Lamba, 2012; McCullough et al., 2011). Educational efforts will serve to help produce an operational workforce that will use these data appropriately for patient-centric results (Bukic et al., 2022; Lee et al., 2015). So, the last one on this list would be how pharmacogenomics can give an important contribution to a new field in medicine nowadays-precision medicine. Pharmacogenomics will aid in utilizing genetic information to make a more precise, individualized, and optimal treatment plan for each patient while making health care more efficient in reducing the 'trial-and-error' prescriptions of drugs (Sangeeta, 2019; Ranade, 2022). This should, in turn, produce better health outcomes, lesser health costs, and a better outcome in terms of patient satisfaction (Pastorino et al., 2021).

2. Pharmacogenomics in Clinical Practice

Pharmacogenomics dramatically improves the efficacy of drugs in patients by basing drug choices and dosing on a patient's genetic background. It is this personalized care in medicine that enables health care providers to predict how patients will be expected to respond to various drugs. This leads to the optimization of therapeutic response and reduction of the adverse drug reaction (ADRs) (Miñarro-Giménez et al., 2014; O'Donnell et al., 2017; Crews et al., 2012). This is one of the basic ways that pharmacogenomics improves drug efficacy; this is through the discovery of genetic variations that can modify drug metabolism. In simpler words, differences within the genes encoding drug metabolizing enzymes can cause alterations in either the rate or the extent at which a drug is metabolized by the body. Knowledge of these genetic factors aids clinicians in choosing medicines that are more likely to be effective for any patient, thus improving efficacy at the time of treatment (Crews et al., 2012; Patrinos, 2023). For example, in hypertension treatment, pharmacogenomics data could guide the doctors to withhold lesser strength anti-hypertensive drugs and instead prescribed those compatible with the drug metabolism of a patient. (O'Donnell et al., 2017; Luzum et al., 2017).

Figure 2. Pharmacogenomic Cycle for Continuous Improvement

Additionally, pharmacogenomics contributes extensively to minimizing ADRs, an alarming phenomenon on the pharmacotherapy scene. For health care providers, genetic testing helps in identifying at-risk patients who may be using harmful drugs. For instance, certain genetic markers indicate that there is a greater likelihood of reactions to potentially dangerous drugs that are similar or even worse than that of warfarin and clopidogrel. Thus, safer prescription is established (Patrinos, 2023; Filipski et al., 2017; Chen et al., 2022). This positive attitude will further enhance patient safety while helping improve adherence to the regimen of treatment administered as most patients are least likely to experience debilitating side effects that may lead to discontinuation of therapy in them (Al-Qerem et al., 2021; Jarvis et al., 2022).

Implementation of pharmacogenomic testing in clinic has proven to significantly improve drug management in clinics. Research has indicated that infusion of pharmacogenomic data into clinical decision support systems has modified prescribing practices to be more individualized and targeted (Miñarro-Giménez et al., 2014; O'Donnell et al., 2017; Luzum et al., 2017). For example, the Pharmacogenomics Research Network has identified a few of the successful implementations across different health care systems and demonstrated the power of pharmacogenomics to improve patient outcomes (Luzum et al., 2017; Jarvis et al., 2022). There is also an educational dimension of pharmacogenomics. As healthcare providers learn more

about the principles of pharmacogenomics, they can understand genetic test results and translate this into clinical practice (Pisanu et al., 2014; Rahma et al., 2020). Increased competency among providers helps to build a healthcare environment in which pharmacogenomics can be added into routine patient care and, therefore, can lead to enhanced drug efficacy and safety (Crews et al., 2012; Bature, 2024). Pharmacogenomic biomarkers are important in clinical decision-making because they provide information about how genetic variations affect an individual's response to drug therapy. Biomarkers are increasingly being integrated into the practice of medicine to tailor drug therapy, improve efficacy, and reduce ADRs. Several important pharmacogenomic biomarkers are already in current use in various therapeutic fields, particularly in oncology, psychiatry, and cardiology.

Table 1: Pharmacogenomic Biomarkers and Clinical Applications.

Biomarker	Associated Gene(s)	Clinical Application	Example Drugs Affected	Reference
CYP2D6	CYP2D6	Drug metabolism and efficacy prediction	Antidepressants, opioids	Crews et al., 2012
TPMT	TPMT	Toxicity prediction for thiopurine drugs	Azathioprine, mercaptopurine	Schuck & Grillo, 2016
HLA-B*57:01	HLA-B	Hypersensitivity reaction risk	Abacavir	Vivot et al., 2015
KRAS Mutation	KRAS	Eligibility for targeted cancer therapy	Cetuximab, panitumumab	Tang, 2019
CYP2C19	CYP2C19	Efficacy and safety of proton pump inhibitors, clopidogrel	Omeprazole, clopidogrel	Hicks et al., 2019
UGT1A1	UGT1A1	Irinotecan toxicity prediction in cancer therapy	Irinotecan	Schuck & Grillo, 2016
CYP3A5	CYP3A5	Drug metabolism for immunosuppressants	Tacrolimus	Eadon et al., 2018
SLCO1B1	SLCO1B1	Statin-associated myopathy risk	Simvastatin	Crews et al., 2012
DPYD	DPYD	Fluoropyrimidine-associated toxicity risk	Capecitabine, 5-Fluorouracil	Hicks et al., 2019

One of the most important biomarkers in pharmacogenomics is CYP2D6, which encodes a cytochrome P450 enzyme that metabolizes many drugs, including antidepressants, antipsychotics, and opioids. The different alterations in the CYP2D6 gene can categorize patients as poor, intermediate, extensive, or ultra-rapid metabolizers, significantly changing the efficacy and safety associated with drugs (Tang, 2019; Schuck & Grillo, 2016). For example, patients with diminished CYP2D6 activity will not benefit fully by conventional dose levels of drugs that need titration doses or other types of therapies (Schuck & Grillo, 2016).

Other relevant markers include TPMT-thiopurine S-methyltransferase - which is necessary for metabolizing certain thiopurine drugs drugs used for the treatment of diseases, such as leukemia and some autoimmune diseases. In contrast, genetic variations within the TPMT gene predispose

to high toxicity in individuals who are treated with regular doses of thiopurines; hence, genetic testing should be considered an essential approach to dosing decisions (Tang, 2019; Schuck & Grillo, 2016). Conversely, UGT1A1 polymorphisms have been shown to be of great importance concerning irinotecan chemotherapy for patients with colorectal cancer since some genetic variations in this locus predict severe neutropenia (Schuck & Grillo, 2016). In oncology, the selection of targeted therapies is dependent on biomarkers such as KRAS and BRAF mutations. For instance, in colorectal cancer patients, the presence of a KRAS mutation indicates that they are unlikely to benefit from anti-EGFR therapies, which guides oncologists in choosing the right treatment options (Tang, 2019). Further, in somatic mutation, for HER2-positive breast cancer, the eligibility of these patients to be administered trastuzumab therapy should consider the status of the patients' HER2 and many more, as cited by Guedes et al., 2021.

In psychiatry, pharmacogenomic testing of biomarkers for CYP2C19 and CYP1A2 can help tailor antidepressive therapy. Variants within these genes may influence metabolism of common antidepressants with an impact on treatment outcomes as well as side effects risk profiles (Lin et al., 2021). Another highly established pharmacogenomic biomarker is the HLA-B 57:01 allele that predicts hypersensitivity reactions to the antiretroviral drug abacavir. Testing for this allele before prescribing abacavir will prevent severe adverse reactions and enhance the safety of the patient (Vivot et al., 2015). There are organizations that have come up with actionable guidelines to ensure the support of integration of pharmacogenomic biomarkers into clinical practice, such as the Clinical Pharmacogenetics Implementation Consortium and the Dutch Pharmacogenetics Working Group (Eadon et al., 2018). These guidelines make sure data from pharmacogenomics are used more effectively in the prescription of drugs to achieve more customized and effective care.

3. Pharmacogenomics in Microbial Practice

The major ways that pharmacogenomics may potentially alter management of infectious disease include discovery of genetic markers that will predict how a patient could react to a particular drug. One famous among them is the HLA-B5701 allele, as it had been associated with hypersensitivity reactions related to the administration of the antiretroviral drug known as abacavir. This is important in that testing for this allele before the start of the treatment is effective in averting severe adverse reactions and, as such, improves the safety of patients, thus ensuring greater adherence to treatment (Haas et al., 2011). Polymorphisms in the MDR1 gene, in particular c.3435C/T, can also predict response to antiretroviral therapy, hence clinicians can tailor treatment regimens for maximum efficacy (Haas et al., 2011).

Pharmacogenomics also allows clinicians to choose the appropriate antibiotics in the face of increasing antimicrobial resistance. Understanding the genetic variation that affects the metabolism and efficacy of the drug enables health professionals to make more rational choices as to which antibiotic may be likely to be effective for a patient. It is even more so during the treatment of multidrug-resistant infections when traditional empirical therapy fails to work well (Mandlik et al., 2017). In general, this means that pharmacogenomic testing should be

incorporated into clinical practice so that antibiotics can be used more selectively and effectively for better patient outcomes and the reduction of the burden of resistance (Mandlik et al., 2017).

Besides guiding on drug choice, the knowledge also aids in dosing strategies. This is because genetic variation determines the rate at which a drug can be metabolized; something that varies widely from one person to another. For example, patients who have particular polymorphisms of drug-metabolizing enzymes will require the dosage to be adjusted in order to achieve therapeutic levels without resulting in toxicity (Micaglio et al., 2021). This personalization of dosing is highly beneficial for vulnerable populations, like elderly and comorbid patients, who are most likely to be at risk for ADRs (Micaglio et al., 2021). This is further stressed by the fact that pharmacogenomics can help develop new therapies. Research is the area where pharmacogenomics would assist researchers to identify factors genetically determined leading to resistance to treatment hence new drug design targeting specific profiles based on genetics, it assists patients with hard-to-treat infections (Olivier & Williams-Jones, 2014). Especially in the area of neglected and emerging infectious diseases, pharmacogenomics can give clues to develop effective therapies targeted for affected populations (Olivier & Williams-Jones, 2014).

Table 2: Benefits and Barriers to Pharmacogenomics Implementation.

Benefits	Barriers	Reference
Improved drug efficacy and reduced ADRs	High cost of pharmacogenomic testing	Mahmutović et al., 2018
Enhanced personalization of treatment	Limited provider education and awareness	Abdela et al., 2017
Potential to address antimicrobial resistance	Lack of universal access to testing	Mandlik et al., 2017
Development of targeted therapies for diseases	Ethical and privacy concerns	Vijverberg et al., 2010
Integration into clinical decision support tools	Implementation challenges in routine clinical use	Crews et al., 2012

But this is not the extent of the reaches of pharmacogenomics since it extends to the spectrum from viral to bacterial infections; for instance, there is a genetic basis that guides treatment for drug-resistant tuberculosis in terms of informing efficacy for subsequent treatment regimens for tackling a very highly profiled public health threat within our communities (Mandlik et al., 2017). Pharmacogenomics impacts antimicrobial therapy in one of its chief ways through genetic polymorphism in drug-metabolizing enzymes. Genetic variances in CYP2C19 and CYP2D6 among many others can be rather a vital factor in the metabolically active nature of a few antibiotics; thus the drug efficacy may differ along with risk for toxicity increasing Daly (2023). These genetic factors will be helpful to clinicians in the selection of antibiotics and dosing regimens to maximize the treatment of individual patients and therefore increase their likelihood of successful outcomes without raising their risk of adverse drug reactions (Lee et al., 2023).

This pharmacogenomic testing would be very useful in informing the choice of antimicrobial agents given the increasing resistance to these antimicrobial agents. For example, traces of genetic markers related to resistance can be found in the host and pathogens. Such knowledge

can lead to appropriate antibiotics, especially in instances when empirical traditional therapy might not work due to resistance (Relling & Evans, 2015). Integration of such data with pharmacogenomic considerations may lead to improved and more targeted and appropriate usage of antimicrobials that are much more required for the growing challenge of combating the emerging threat of AMR. According to Relling and Evans (2015),

Pharmacogenomics may also be exploited for new antimicrobial drugs designing. With such information, new drugs will be identified that target specific genetic profiles, thereby increasing treatment opportunities in patients infected with drug-resistant infections (Relling & Evans, 2015). This is considerably essential in the context of neglected and emerging infectious diseases; pharmacogenomics is informative in terms of designing drugs that are targeted at affected populations (Relling & Evans, 2015). It can also be noted in hypersensitivity reactions to antibiotics. The genetic testing of markers like HLA-B5701 helps predict adverse reactions to drugs such as abacavir, and hence it can be prescribed with caution to those patients who can tolerate it without major side effects (Aung et al., 2014). This proactive approach also increases patient safety and is a better adherence to the treatment regimen because patients will be less likely to experience debilitation side effects that might result in discontinuation of therapy (Aung et al., 2014).

Additionally, the development of guidelines and decision support tools concerning pharmacogenomics is also very important for the integration of pharmacogenomic data into clinical practice. Projects such as Ubiquitous Pharmacogenomics (U-PGx) focus attention on pharmacogenomics across the different settings of the health care sectors and enable better information actionable by prescribing authorities regarding antimicrobial therapy. That ultimately results in a far more personalized and effective system for antimicrobial therapies because this pharmacogenomic knowledge gets easily infused into actual practice through such clinical routine procedures (Blagec et al. 2018).

4. Personalized Healthcare: Bridging Clinical and Microbial Applications

One of the significant benefits is that pharmacogenomics can become an integral part of clinical practice by tailoring drug selection and dosage to an individual's genetic composition. For instance, the pharmacogenomic test will identify whether genetic variants impact drug metabolisms, for example through CYP450 family. Such variants will significantly modify how patients will respond to antibiotics and antiviral agents Frick et al. (2018).Frick et al., 2016). Understanding these genetic factors will help healthcare providers optimize the selection and dosing of drugs, enhancing therapeutic efficacy while minimizing the risk of toxicity (Hinderer et al., 2017).

Table 3: Strategies for Integrating Pharmacogenomics into Clinical Practice.

Strategy	Description	Reference
Education and Training	Integrate pharmacogenomics into medical curricula and continuing education programs	Bukic et al., 2022

Development of Clinical Guidelines	Use guidelines from CPIC and other organizations to standardize pharmacogenomic applications	Caudle et al., 2014
Integration into Electronic Health Records (EHR)	Embed pharmacogenomic data and decision support tools into EHR systems	Hicks et al., 2016
Accessibility Initiatives	Provide subsidies and programs to enhance access to pharmacogenomic testing	Mandlik et al., 2017
Multidisciplinary Collaboration	Foster collaboration among geneticists, pharmacists, and clinicians to ensure comprehensive care	Dunnenberger et al., 2016

Furthermore, the convergence of pharmacogenomics with microbial genomics will offer a more subtle approach in the management of infectious diseases. For example, knowledge of the genetics of the reason for resistance to antimicrobials in pathogens can guide antibiotic choice as well as inform a treatment decision; this would be particularly so in light of the rising cases of antimicrobial resistance, as traditional empirical treatment may no longer be appropriate (Brown-Johnson et al., 2021; Saulsberry et al., 2021). Clinicians may then be able to use pharmacogenomic data in combination with the microbial genomic data in determining which antibiotics are likely to work for any given patient so making treatment outcomes better and lowering the burden of resistance (Saulsberry et al., 2021).

4.1. Clinical decision support systems

CDSS are significant to ensure that pharmacogenomics may eventually be integrated into routine clinical practice. These systems will thus be in a position to present healthcare providers with actionable insights that may be based on pharmacogenomic data, helping them make prescribing decisions better (Rasmussen et al., 2019; Hoffman et al., 2020). Studies have shown that the majority of physicians require tools that would integrate genetic information into the practice of medicine, hence showing the benefit in using such tools, specifically pharmacogenomic CDSS, in clinical decision-making (Hinderer et al., 2017; Rasmussen et al., 2019). The integration of pharmacogenomic data into EHRs will provide healthcare providers with relevant genetic information at the point of care, thereby further enhancing treatment personalization (Hoffman et al., 2020).

Education and Training. Pharmacogenomics also needs to become part of education and training for healthcare professionals to help assure the successful implementation of personalized medicine. For example, pharmacists are in a very strategic position to play this integration role because they will be able to provide pharmacogenomic counseling and support medication therapy management (Frick et al., 2016; Balogun, 2024). If the healthcare system equips healthcare providers with the knowledge and skills to interpret pharmacogenomic data, then it can improve its ability to use this information to optimize patient care (Bukic et al., 2022). Therefore, personalized medicine can lead to improved treatment outcomes through enhanced efficacy and safety with the use of pharmacogenomic information to make decisions on which types of antimicrobial therapy may be used. In one such case, knowledge regarding drug metabolism in relation to genetic variation is important because it helps a physician make the right decision over the appropriate antibiotic to prescribe to a particular patient Bissonnette & Bergeron (2012). More than that, metagenomic analysis can rapidly identify pathogens and their

resistance profiles so that antimicrobial treatments can be adapted by healthcare providers more effectively (Nakamura et al., 2011). Such an approach is especially relevant in the context of growing antibiotic resistance, where empirical treatments would fail (Chang et al., 2022).

Furthermore, personalized medicine can help make health care systems better prepared for epidemics of infectious diseases. Health care systems can assess individual risk factors and the genetic predispositions to determine targeted vaccination strategies and measures of prevention based on vulnerable populations (Chang et al., 2022). For example, in the COVID-19 pandemic, personalisation was applied to identify people who are more likely to suffer from severe disease, thereby making it possible to prioritize the vaccination and treatment plans for them (Liu et al., 2021). In this manner, such an anticipatory measure not only brings about improvement in the patient's outcome but also works towards greater public health interests by reducing the spread of infectious diseases and their resultant morbidity (Li et al., 2022).

It becomes better managed and has good outcomes because of unique genetic and environmental factors that would influence the progression of a disease and the response to treatment. Personalized medicine can further improve the management of diabetes or hypertension by identifying one's specific set of medications and lifestyle interventions required based on his/her genetic profile (Bitar & Alismail, 2021). This may maximize therapy adherence and optimize therapeutic benefits ultimately leading to better disease control and quality of life (Bitar & Alismail, 2021). In addition, telehealth and remote monitoring technologies have supported the delivery of personalized care for chronic diseases, especially in the time of the COVID-19 pandemic. Continuous monitoring of health parameters with the proper adjustments of the treatment plans based on real-time data contributes to better engagement and outcomes from the patient (Bitar & Alismail, 2021). Further personalized health interventions like tailored diet and exercise recommendations can be developed based on individual health data, enhancing the management of chronic diseases further (Bitar & Alismail, 2021).

5. Ethical and Regulatory Considerations

One of the most ethical issues is that of informed consent. The patients should be given adequate information regarding the nature of pharmacogenomic testing, which includes benefits, risks, and limitations. This is important because pharmacogenomic tests may reveal sensitive information about an individual's predispositions to various health conditions, which might not only affect drug response but also other health conditions (Shah et al., 2010; Haga et al., 2012). They should be informed about matters they agree to in order to protect them and the integrity of the healthcare system. Privacy and confidentiality also feature among the major ethical concerns. The genetic information gleaned from pharmacogenomic testing is highly sensitive and easily liable to abuse. It may be accessed by people who are not authorized to have this information, and then the risk of genetic discrimination by employers or insurance companies is on the rise (Vijverberg et al., 2010). Conclusion: Strong data protection methods will be required to ensure information about the patient and then use it only for what is intended: healthcare enhancement.

Another ethical issue revolves around access. When genetic testing by pharmacogenomics becomes an integral part of clinical practice, another issue that emerges is inequalities in terms of access to the available services. Those who lack adequate access to healthcare resources or are from disadvantaged backgrounds will not have equal opportunities for pharmacogenomic testing and benefits therefrom (Bature, 2024; Mitropoulou et al., 2014). This raises ethical issues as far as healthcare equity goes and whether it is aggravating health disparities. Pharmacogenomic services should be universally available to all patients by socio-economic status or other geographical location.

The other aspect has to do with the possibility of over-medicalization while ignoring the implications of the genetic determinism. High light on genetic factors might bring in the missing view on environmental and social determinants of health. It leads to a focus that seems too narrow to just involve genetic testing in neglect of more holistic care of a patient with regard to a larger context in which health and disease reside (Hansson & Chadwick, 2011). The ethical frameworks should thus be established to balance the benefits of pharmacogenomics with the need to address the multifaceted nature of health and disease. Pharmacogenomics has also raised several questions on the accountability of clinical decision making. Greater reliance on the genetic basis for treatment decisions has made the healthcare professional susceptible to committing errors in the interpretation and application of pharmacogenomics data. Therefore, guidelines must be formulated and followed with extensive training for these healthcare providers in order to avoid pitfalls as a result of misinterpretation of the pharmacogenomic results (Shah et al., 2010; Bature, 2024).

5.1. Identifiability of Genomic Data:

Genomic data is specific to an individual and may be treated as a sort of unique identifier. Other health data can be de-identified or aggregated, but genomic data cannot be properly de-identified since its nature itself is such that it cannot be (Honkela et al., 2018; Raisaro et al., 2014). In addition, access of publicly accessible information can help in re-identifying anonymized genomic information. Such have posed potential risks of unauthorized access and misuse (Rogith et al., 2014). The linkage of genomic information might also expose sensitive information related to individuals' predispositions to certain conditions, and such information exposes individuals to discrimination or stigma as a result (Gürsoy, 2022; Schneider & Tkachenko, 2018).

5.2. Linkage with Other Personal Data:

There is an emerging concern about whether genomic data will be linked to other types of personal data, such as clinical data and billing information. It has been established that the patients are most concerned by how their genomic data would be combined with identifiable information, which increases the possibility of privacy breaches and confidentiality (Rogith et al., 2013; Rogith et al., 2014).

5.3. Data Sharing and Consent:

It is because of sharing data that ethical questions rise about data sharing in genomic research. Even though data sharing accelerates the progress about precision medicine, the question of informed consent does seem to arise. Data sharing does accelerate the progress for precision

medicine, but so does this problem of informed consent come up. The implications of sharing genomic data among patients might be less understood, which implies the risks of re-identification and misuse by third parties (McGuire et al., 2011; Bonomi et al., 2020). Proper understanding of the risks and benefits associated with the sharing of data is critical in developing trust in genomic research.

5.4. Genetic Discrimination:

The biggest fear associated with genomic data is genetic discrimination. The risk of utilizing such information against them by the employers or insurance companies keeps people at bay and results in denial of employment or coverage (Honkela et al., 2018; Schneider & Tkachenko, 2018). This entails colossal legal protection from genetic information-based discrimination.

5.5. Technological Fixes and Constraints:

There have been development phases for the privacy-preserving technologies about genomic data in forms such as differential privacy and homomorphic encryption, which yet has still not been fully secure genomics in place. Arguing discussions about whether this would result in data to privacy actually allowing meaningful analytical scope existed in literature - that being those of Ayday (2016); Wang et al., (2014) and Tang et al., (2016). Ensuring a delicate balance between utility and privacy has been the biggest challenge facing the field of genomics.

5.6. Public Trust and Transparency:

Loss in the public trust about how genomic data is treated has increased with more and more health data breaches, among other things, and also because of increased usage of genomic databases for law enforcement purposes (Grishin et al., 2021). The way data will be used and shared on genomic data must be clearly communicated to the patients and the public about the handling of data. Communication like this helps gain trust, according to Gürsoy, 2022 and Grishin et al., 2021.

6. Technological Innovations and Future Perspectives

6.1. Next-Generation Sequencing (NGS):

The advent of next-generation sequencing technologies has revolutionized the field of genomics by enabling rapid and cost-effective sequencing of entire genomes. This technology allows for the identification of genetic variants that influence drug metabolism and response, facilitating the development of personalized treatment plans (Zhang et al., 2013; Rothstein, 2012). As NGS becomes more accessible, it is expected to play a pivotal role in routine pharmacogenomic testing, allowing clinicians to tailor therapies based on individual genetic profiles (Wheeler et al., 2012).

6.2. Clinical Decision Support Systems (CDSS):

In integrating pharmacogenomic data into electronic health records, for example, clinical decision support systems are important in promoting personalized medicine. These clinical

decision support systems give health providers actionable information based on the genetic information of the patient in order to guide drug selection and dosing (Hicks et al., 2016; Nishimura et al., 2015). For example, the Vanderbilt PREDICT project is a very successful CDSS that utilizes pharmacogenomic data in informing clinical decision-making processes. As a result, this reduces adverse drug reactions and improves therapeutic outcomes (Pulley et al., 2012).

6.3. Pharmacogenomic Identity Cards:

Novelties like the pharmacogenomics identity card, popularly called PPM card in Thailand, have enabled how technology could make the practical application of pharmacogenomics at clinical practice levels. This card immediately lets a health professional obtain access to a patient's pharmacogenomic profile to facilitate a speedier implementation of precision medicine at the bedside level (Biswas et al., 2022). Such initiatives can also be used as examples by other regions looking to implement pharmacogenomics in clinical practice.

6.4. High-Throughput Genotyping Technologies:

High-throughput genotyping technologies have increased the ability of researchers to analyze genetic changes across large populations. There is a possibility of better polymorphisms associated with drugs' response, hence more effective as well as safer therapeutic strategies being developed (Zhang et al., 2013; Kohler et al., 2014). The huge number of genetic studies for uncovering complex relationships between genetic variants and the efficacy of drugs is paramount.

6.5. Bioinformatics Tools:

Sophisticated bioinformatics tools to produce such huge data sets generated through genomic studies will help manage and interpret them. Through such tools, researchers and clinicians will be able to analyze genetic data, identify appropriate pharmacogenomic markers, and determine the implications of these markers on drug therapy (Amanat, 2024; Geeth, 2024). As the discipline of bioinformatics grows further, it will further aid in the integration of genomic data into clinical practice.

6.6. Education and Training Technologies:

Another aspect via which pharmacogenomics enters health care is the training and education of health practitioners. Due to the progression in learning technologies such as the e-learning platforms and simulation-based training, there has been the ability to enhance the knowledge and skills of clinicians concerning pharmacogenomics (Lim, 2023; Gammal et al., 2022). For that reason, there is the need for education in respect to how health practitioners ought to decode pharmacogenomic data into making actual clinical decisions.

6.7. Collaboration and Multidisciplinary Approaches:

Another technological advancement that integrates with healthcare is the establishment of multidisciplinary clinics that will have pharmacogenomic services. These clinics bring together geneticists, pharmacists, and clinicians to provide comprehensive care leveraging the insights of pharmacogenomics. This kind of approach is integral to the complexities of personalized

medicine and ensuring that every patient receives optimal care for their genetic profile (Dunnenberger et al., 2016).

6.8. Integration of Artificial Intelligence and Machine Learning:

One promising direction in future research is the application of machine learning and deep learning techniques in pharmacogenomics. These technologies may potentially analyze complex datasets and derive hidden patterns to predict drug response based on genetic and clinical biomarkers Lin et al. (2021) Lin et al., 2020). This kind of research should be devoted to predictive algorithms that can support genetic variant investigation and its interactions with various treatments to improve personalization treatment strategies (Lin et al., 2018).

6.9. Education and Training:

Demand in pharmacy and medical curricula, very high to boost education with regard to teaching in a comprehensive approach on pharmacogenomics: Various research works presented earlier establish that there exist very large-scale institutes around the globe without enough suitable pharmacogenomics training and leading their health institutions to have lesser capabilities to implement personal healthcare solutions (Bukic et al., 2022; Mahmutović et al., 2018). Future research studies should emphasize the development of educational programs that will equip healthcare professionals with knowledge and skills in the interpretation of pharmacogenomic data and its application in clinical practice (Lim, 2023; Kuželiki et al., 2019).

6.10. Patient Perspectives and Engagement:

Understanding patient attitudes and perceptions is crucial for effective implementation of pharmacogenomics in healthcare. The aim of the research should be as follows: how patients perceive the idea of pharmacogenomics, any issues with privacy and discrimination, and benefits of patient-specific treatment (Saulsberry et al., 2021; Sangeeta, 2019). Patients can be involved with the development and implementation process of pharmacogenomic services with improved acceptance and adherence toward the patient-specific therapies.

6.11. Development of Polygenic Risk Scores (PRS):

The advancement of pharmacogenomic polygenic risk scores continues to be a major area of research. Consequently, the development of PRS across a wide range of diseases has not yet been explored in depth toward predictions of drug response (Singh, 2024). These methods require further sharpening, besides validation of clinical utility in pharmacogenomics.

6.12. Ethical, Legal, and Social Implications (ELSI):

With further integration of pharmacogenomics into the healthcare system, it is also important that it be used with ethical considerations about its legal and social implications. Further research is warranted about genetic discrimination and privacy issues in the use of pharmacogenomics as well as what is required for robust consent processes (Volpi et al., 2018; Hicks et al., 2019). This requires the development of guidelines and policies that protect the rights of the patients while promoting responsible usage of genomic data, thereby instilling public trust in pharmacogenomics.

6.13. Implementation Science:

Future research should focus on practical implementation of pharmacogenomics in the clinical environment. This ranges from knowledge gaps among practitioners, system-level barriers to implementation, and the call for clinical decision support tools for the process (Giacomini et al., 2021; Chumnumwat et al., 2019). Such studies will be useful in providing avenues for effective integration of pharmacogenomic testing into general clinical practice, thus fully harnessing its benefits in diverse settings.

7. Conclusion

Pharmacogenomics could change health care as the treatment of a person can be tailored to his or her genetic profile. It enhances patient care, decreases ADRs, and addresses problems such as antimicrobial resistance, as it is feasible to integrate this technology into clinical and microbial practice. However, enormous obstacles must be overcome before pharmacogenomics can become a reality: these are the lack of education in the health care providers, ethical and privacy issues, the cost, and unequal access to testing. Such joint efforts by the relevant stakeholders will be of a duration to overcome such obstacles and make the best pharmacogenomics a success. Development of strong clinical guidelines, better education and training programs, and pharmacogenomics data in electronic health records are the need of the hour. It is very evident that, in the further evolution of technology and research, pharmacogenomics would find its place in delivering personal medicine in ways of more accurate, effective, and equitable care. Such advancement does not simply constitute a scientific revolution but one that would result in a paradigm shift on how one practices medicine-from general to patient-specific and hence better health outcome.

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Author contributions

Every co-author took part in the editing of the manuscript, the gathering of literature, and the construction of tables and figures. The corresponding author assisted the first author in drafting the original manuscript. Final permission is granted to each author before the paper is submitted to a journal for publication.

Conflict of Interest

The authors declare no conflict of interest, financial or otherwise.

Ethical Approval

Not Applicable

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