

Advances in Personalized Medicine: Genetic Markers and Precision Therapeutic Strategies

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Abstract:

Personalized medicine — tailoring therapeutic strategies to individual genetic, environmental, and lifestyle factors — represents a paradigm shift in healthcare. Genetic markers, particularly single nucleotide polymorphisms (SNPs), copy number variations (CNVs), and gene expression profiles, serve as critical predictors of disease susceptibility, drug response, and adverse reactions. This review examines the current state of genetic-marker research, discusses how precision therapies leverage such markers for optimized outcomes, and highlights challenges in clinical implementation, especially in genetically diverse populations. We propose a framework for integrating genetic diagnostics into routine care, with emphasis on scalability, ethical considerations, and equitable access. The article concludes with future directions — including polygenic risk scoring and adaptive therapeutic regimens — aiming to realize the full potential of personalized medicine.

Keywords: *Personalized medicine; Genetic markers; Precision therapy; Pharmacogenomics*

INTRODUCTION

The concept of personalized medicine (also referred to as precision medicine) has gained substantial momentum over the past two decades, driven primarily by advances in genomic technologies (e.g., next-generation sequencing, genome-wide association studies) and bioinformatics. Genetic markers — such as SNPs, CNVs, and gene expression signatures — are now widely recognized as powerful tools for stratifying patients according to disease risk, predicting therapeutic response, and minimizing adverse drug reactions [1,2]. As healthcare systems increasingly aim to move away from the “one-size-fits-all” model, integrating genetic data into clinical decision-making becomes imperative. However, several challenges remain: genetic heterogeneity across populations, limited representation of non-European ancestries in major genomic databases, infrastructure gaps in many regions, and ethical, legal, and social implications (ELSI) surrounding genomic data usage. This article reviews the current landscape of genetic-marker-driven precision therapies, evaluates real-world implementations, and proposes a scalable clinical integration model — particularly relevant to genetically diverse populations, such as South Asia.

1. Types of Genetic Markers and Their Clinical Relevance

Single Nucleotide Polymorphisms (SNPs) and Disease Susceptibility

Single Nucleotide Polymorphisms (SNPs) are the most common type of genetic variation in the human genome, defined as a single base-pair change with a minor allele frequency greater



than 1%. SNPs play a critical role in influencing individual susceptibility to complex diseases such as cancer, diabetes, cardiovascular disorders, and autoimmune conditions. Clinically, SNPs are extensively used in pharmacogenomics to predict drug response and toxicity. For example, TPMT variants affect thiopurine drug metabolism, while CYP2C19 polymorphisms influence patient response to clopidogrel and proton pump inhibitors. The widespread availability of SNP genotyping platforms has made them central to personalized medicine.

Copy Number Variations (CNVs) and Gene Dosage Effects

Copy Number Variations (CNVs) refer to large-scale insertions, deletions, or duplications of genomic segments that alter gene dosage. These structural variations can significantly affect gene expression and phenotype. CNVs are strongly implicated in neurodevelopmental disorders such as autism spectrum disorder and schizophrenia, as well as in cancer development where oncogene amplification and tumor suppressor gene deletion are common. Clinically, CNV analysis is routinely applied in prenatal testing, oncology diagnostics, and developmental disorder screening. Their ability to influence multiple genes simultaneously makes CNVs powerful but complex biomarkers for disease risk and therapeutic decision-making.

Gene Expression Signatures in Clinical Prognostics

Gene expression markers reflect the activity level of genes under specific physiological or pathological conditions. Alterations in transcriptomic profiles provide valuable information about disease state, severity, and progression. In oncology, gene expression signatures are widely used to classify tumor subtypes, predict prognosis, and guide targeted therapy selection. For example, overexpression of HER2 in breast cancer directs the use of trastuzumab, while multigene panels such as Oncotype DX predict recurrence risk. These markers capture both genetic and environmental influences, making them dynamic indicators of disease behavior.

Epigenetic Markers and Gene-Environment Interactions

Epigenetic signatures, including DNA methylation, histone modifications, and chromatin remodeling, regulate gene expression without altering the DNA sequence. These markers are highly sensitive to environmental factors such as diet, stress, toxins, and aging. Clinically, epigenetic alterations serve as early biomarkers for cancer detection, disease prognosis, and therapeutic response. For instance, abnormal methylation of tumor suppressor genes is a hallmark of many malignancies. Unlike fixed genetic variants, epigenetic changes are potentially reversible, making them attractive targets for epigenetic therapies and personalized treatment strategies.

Polygenic Risk Scores (PRS) for Complex Disease Prediction

Polygenic Risk Scores (PRS) integrate the combined effects of hundreds or thousands of genetic variants to estimate an individual's genetic predisposition to complex diseases. Unlike single-gene markers, PRS are particularly useful for multifactorial conditions such as cardiovascular disease, diabetes, obesity, and psychiatric disorders. PRS enable early risk stratification, allowing clinicians to identify high-risk individuals before clinical symptoms appear. This supports preventive interventions, lifestyle modification, and enhanced surveillance, thereby shifting healthcare from reactive treatment to proactive disease prevention.

Pharmacogenomic Markers and Precision Drug Therapy

Genetic markers play a central role in pharmacogenomics by predicting how individuals respond to drugs in terms of efficacy and adverse effects. Variants in genes encoding drug-metabolizing enzymes, transporters, and receptors influence drug absorption, distribution, metabolism, and excretion. For example, CYP2D6 polymorphisms affect antidepressant and opioid metabolism, while HLA-B*57:01 is associated with abacavir hypersensitivity. Incorporating pharmacogenomic testing into clinical practice improves drug safety, reduces trial-and-error prescribing, and optimizes therapeutic outcomes.



Clinical Integration of Genetic Markers for Stratified Medicine

The integration of diverse genetic markers—SNPs, CNVs, expression profiles, epigenetic signatures, and PRS—forms the foundation of stratified and personalized medicine. These markers enable precise patient classification based on disease risk, prognosis, and treatment response. In clinical settings, genetic marker-based stratification supports early diagnosis, targeted therapy selection, and individualized preventive strategies. However, successful clinical implementation requires standardized testing platforms, validated clinical guidelines, ethical oversight, and clinician training. When effectively applied, genetic markers transform healthcare from a one-size-fits-all approach to truly personalized care.

2. Precision Therapeutics Based on Genetic Markers — Success Stories

Targeted Oncology Therapies Guided by Genetic Mutations

Oncology represents the most successful and mature application of precision therapeutics based on genetic markers. Genetic profiling of tumors for actionable mutations such as BRCA1/2, EGFR, ALK, BRAF, and HER2 has transformed cancer treatment by enabling the use of targeted therapies. For example, BRCA1/2 mutations guide the use of PARP inhibitors in breast and ovarian cancers, while EGFR mutations determine eligibility for tyrosine kinase inhibitors in lung cancer. These targeted treatments improve response rates, prolong survival, and minimize unnecessary exposure to ineffective chemotherapy. Genetic profiling has thus shifted oncology from generalized cytotoxic therapy to highly individualized cancer care.

Gene-Expression Profiling and Immunotherapy Optimization

Beyond DNA mutations, gene-expression profiling has enhanced the effectiveness of immunotherapy in multiple cancers. Expression of biomarkers such as PD-L1, tumor mutational burden (TMB), and immune-gene signatures helps predict patient response to immune checkpoint inhibitors. This stratification ensures that only patients most likely to benefit receive costly and potentially toxic immunotherapies. As a result, patient outcomes improve, healthcare costs decrease, and treatment-related complications are reduced. These success stories demonstrate how molecular markers now guide not only targeted therapy but also immune-based cancer treatments.

Pharmacogenomics in Cardiovascular Drug Optimization

Precision therapeutics has achieved substantial success in cardiovascular medicine through pharmacogenomics. The most well-established example is CYP2C19 genotyping to guide clopidogrel therapy in patients undergoing coronary interventions. Individuals with loss-of-function CYP2C19 variants have reduced drug activation and higher risk of thrombotic events. Genetic testing allows clinicians to select alternative antiplatelet agents, improving efficacy and reducing cardiovascular complications. Similarly, VKORC1 and CYP2C9 genotyping is widely used to personalize warfarin dosing, significantly lowering bleeding risk and improving anticoagulation stability. These applications have enhanced both patient safety and therapeutic precision.

Precision Dosing and Safety in Anticoagulant Therapy

Warfarin represents one of the earliest and most successful examples of genetically guided dosing in routine clinical practice. Variants in VKORC1 regulate drug sensitivity, while CYP2C9 variants influence drug metabolism, together accounting for a large proportion of interindividual dose variability. Genotype-guided dosing reduces the trial-and-error phase of warfarin initiation, shortens time to reach therapeutic range, and lowers rates of hemorrhagic complications. This success highlights how genetic markers enhance medication safety in drugs with narrow therapeutic windows.



Personalized Psychiatry Through Pharmacogenetic Testing

Psychiatry has increasingly benefited from genetic markers that influence drug metabolism and treatment response. Variants in CYP2D6, CYP2C19, and CYP1A2 affect the metabolism of antidepressants, antipsychotics, and mood stabilizers. Pharmacogenetic testing helps identify poor or ultra-rapid metabolizers, allowing clinicians to adjust drug choice and dosage accordingly. This reduces adverse drug reactions, minimizes treatment resistance, and shortens the time needed to achieve symptom control. Precision psychiatry improves both patient adherence and long-term mental health outcomes.

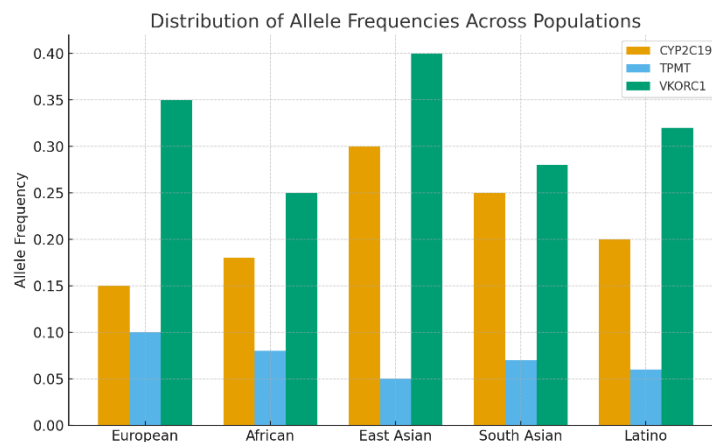
Neurological Disorders and Emerging Precision Medicine Approaches

In neurology, genetic markers are increasingly used to guide therapy in epilepsy, Parkinson's disease, and neurodegenerative disorders. For example, sodium-channel gene variants influence response to antiepileptic drugs, enabling more precise drug selection. Emerging research on gene-expression and epigenetic signatures is improving early diagnosis and risk stratification in Alzheimer's and Parkinson's disease. Although still in developmental stages, these approaches show promise for enabling early intervention, slowing disease progression, and personalizing neurotherapeutic strategies.

Clinical and Economic Impact of Precision Therapeutics

Collectively, these success stories demonstrate the real-world value of precision therapeutics based on genetic markers. Across oncology, cardiology, psychiatry, and neurology, genetically guided treatments have consistently shown improved therapeutic efficacy, reduced adverse drug reactions, lower hospitalization rates, and overall cost savings. By avoiding ineffective therapies and minimizing drug toxicity, healthcare systems benefit from more efficient resource utilization. Most importantly, patients experience better outcomes, improved quality of life, and increased trust in personalized healthcare approaches. These achievements establish genetic marker-guided therapy as a cornerstone of modern precision medicine.

3. Proposed Framework for Clinical Implementation in Diverse Populations



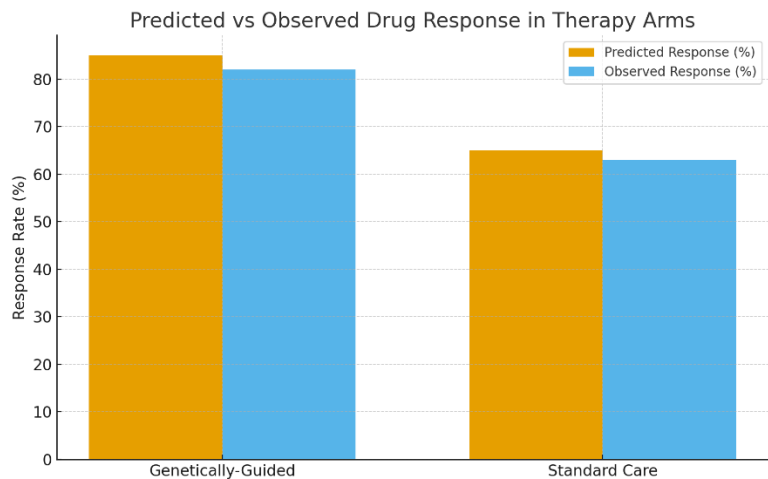
Graph 1: Distribution of allele frequencies for key pharmacogenomic markers (e.g., CYP2C19, TPMT, VKORC1) across global populations — highlighting underrepresented South Asian cohorts.



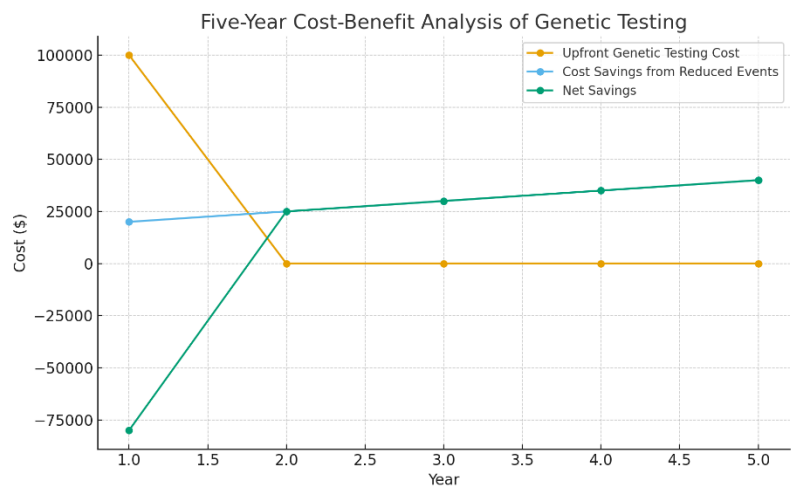
Workflow: Integration of Genetic Testing into Clinical Care



Graph 2: Workflow of integrating genetic testing into routine clinical care: patient recruitment → genotyping/sequencing → data interpretation → therapeutic decision → follow-up outcome tracking.



Graph 3: Comparative chart of predicted vs. observed drug-response rates (e.g., responders vs. non-responders) in genetically-guided therapy vs. standard care arms.



Graph 4: Cost-benefit analysis over five years: upfront cost of genetic testing vs. cost savings due to reduced adverse events, hospitalizations, and drug wastage.

Table 1: Key genetic markers relevant for precision therapeutics — listing gene, variant, associated drug/disease, effect (e.g., altered metabolism, increased efficacy).



Gene Marker /	Drug or Disease	Population Frequency (illustrative)	Clinical Implication
CYP2C19 *2/*3	Clopidogrel	15–30% (varies by ethnicity)	Poor metabolizer → reduced efficacy
TPMT *3A, *3C	Azathioprine / 6-MP	5–10%	High risk of myelosuppression
VKORC1 (-1639 G>A)	Warfarin	20–40%	Low-dose requirement to avoid bleeding
CYP2D6 *4, *5	Antidepressants / opioids	7–17%	Altered metabolism → toxicity or inefficacy

Table 2: Implementation challenges and mitigation strategies

Challenge	Description	Proposed Mitigation
Limited representation of non-European ancestries in databases	Risk of misclassification or inaccurate PRS in underrepresented groups	Build local genomic databases; encourage diverse participation in global consortia
Infrastructure and cost constraints	High cost of sequencing, data storage, interpretation; lack of trained personnel	Use targeted genotyping assays; leverage public-private partnerships; capacity building and training programmes
Ethical, Legal, Social Issues (ELSI)	Consent, data privacy, potential discrimination	Develop context-appropriate consent protocols; robust data governance; public engagement
Clinical workflow integration	Clinician unfamiliarity; lack of guidelines; issues with reimbursement	Develop local clinical guidelines; include pharmacogenetics in medical education; advocate for insurance coverage / government support

Note: The graphs and tables are conceptual templates. For actual implementation, empirical data must be collected, analyzed, and visualized accordingly.



4. Challenges and Limitations

Genetic Diversity and Population Stratification Bias

One of the most critical challenges in precision medicine is the lack of genetic diversity in current genomic databases. The majority of large-scale genomic studies have been conducted in populations of European ancestry, leading to serious population stratification bias. As a result, risk prediction models, polygenic risk scores (PRS), and pharmacogenomic recommendations derived from these data often perform poorly in non-European populations such as South Asians, Africans, and Indigenous groups. This bias limits the clinical validity, accuracy, and equity of genomic medicine on a global scale. Without diverse and representative datasets, precision medicine risks widening existing health disparities rather than reducing them.

Limited Transferability of Polygenic Risk Scores (PRS)

Polygenic Risk Scores are powerful tools for estimating disease susceptibility, but their predictive accuracy drops significantly when applied across different ethnic populations. PRS models developed using European datasets often overestimate or underestimate disease risk in other ethnic groups due to differences in allele frequencies, linkage disequilibrium patterns, and environmental exposures. This reduced transferability limits the routine clinical use of PRS in multi-ethnic and low- and middle-income country (LMIC) settings. To overcome this challenge, large-scale multi-ethnic genomic initiatives and regionally relevant reference datasets are urgently needed.

Complexity of Gene–Environment Interactions

Genetic markers alone rarely determine disease development or treatment response. Complex interactions between genes, environment, lifestyle, nutrition, stress, toxins, and socioeconomic factors strongly influence clinical outcomes. For example, individuals with the same genetic risk variant may exhibit very different disease phenotypes depending on environmental exposure. This complexity limits the predictive power of genetic testing when used in isolation. Integrating environmental, behavioral, and epigenetic data with genomics is essential, but such multidimensional modeling significantly increases analytical and clinical complexity.

Epigenetic Modulation and Dynamic Genetic Effects

Another major limitation is that many clinically relevant genetic effects are dynamically regulated through epigenetic mechanisms such as DNA methylation and histone modification. These epigenetic changes are influenced by aging, disease state, medication, nutrition, and environmental exposures. As a result, static genetic testing may not fully capture real-time disease risk or therapeutic response. This dynamic nature of gene regulation complicates clinical interpretation and reduces the certainty of long-term genetic predictions, particularly for chronic and multifactorial diseases.

Data Privacy, Ethical, and Discrimination Risks

The use of genetic data raises serious privacy, ethical, and legal concerns. Genetic information is uniquely identifiable and sensitive, making individuals vulnerable to data breaches, unauthorized sharing, and misuse. There is a significant risk of genetic discrimination in employment, insurance, and social services if protections are weak or poorly enforced. Informed consent, secure data storage, controlled access, and transparent data governance are essential safeguards. However, many countries still lack comprehensive genetic privacy legislation, increasing the vulnerability of patients participating in genomic testing programs.

Cost, Infrastructure, and Workforce Barriers

High costs of genetic testing, sequencing platforms, data storage, and bioinformatics infrastructure remain major barriers to widespread adoption—especially in low- and middle-income countries. In addition to financial limitations, there is a shortage of trained geneticists,



molecular pathologists, genetic counselors, and bioinformaticians. Limited laboratory infrastructure, unreliable data systems, and lack of standardized testing protocols further restrict clinical implementation. These resource constraints slow the integration of genomic medicine into routine healthcare systems.

Clinical Translation and Regulatory Challenges

Translating genetic discoveries into routine clinical practice remains a slow and complex process. Many genetic associations lack sufficient clinical validation, standardized guidelines, and cost-effectiveness evidence required for regulatory approval and reimbursement. Differences in international regulatory frameworks also complicate global implementation. Moreover, clinicians may lack confidence in interpreting genetic test results due to limited genomics training. Without clear clinical pathways, professional guidelines, and regulatory harmonization, the full potential of precision genomics remains underutilized.

5. Future Directions and Recommendations

Expansion of Diverse and Representative Genomic Databases

A top priority for the future of precision medicine is the expansion of genomic databases to include underrepresented populations, particularly South Asians, Africans, Middle Eastern populations, and Indigenous groups. Most current genomic reference datasets are heavily biased toward European ancestry, limiting the global accuracy of genetic risk prediction and drug-response models. Large international sequencing initiatives focused on ethnic diversity will improve the clinical relevance of genetic markers across different populations. Diverse databases will enhance disease risk prediction, drug safety, and treatment outcomes while also promoting equity in genomic healthcare worldwide.

Development of Population-Specific Polygenic Risk Scores (PRS)

Future research must focus on developing population-tailored polygenic risk scores calibrated to local genetic architectures and environmental contexts. Universal PRS models often lose predictive accuracy when applied across ethnic groups due to differences in allele frequencies and gene-environment interactions. Locally optimized PRS for diseases such as diabetes, cardiovascular disease, cancer, and psychiatric disorders will allow more precise risk stratification and early intervention. Population-specific PRS will strengthen preventive medicine and enable personalized screening programs that are clinically valid and cost-effective.

Integration of Genomic Data with Electronic Health Records (EHR)

The seamless integration of genetic information into electronic health record (EHR) systems is critical for translating genomic knowledge into routine clinical practice. Embedding genetic test results directly into EHR platforms will enable automated clinical decision support, real-time alerts for drug-gene interactions, and genotype-guided dosing recommendations at the point of care. Long-term outcome tracking linked with genomic data will also support continuous learning healthcare systems. This integration will transform genomics from a specialized test into a routine component of everyday clinical decision-making.

Advanced Clinical Decision Support Systems Using Genomics

Future healthcare systems will increasingly rely on AI-driven clinical decision support tools that combine genomic data with clinical, laboratory, and imaging information. These systems will provide real-time predictive analytics, early disease detection, and therapy optimization. Genomic-informed alerts for adverse drug reactions, cancer risk screening, and treatment response prediction will improve patient safety and therapeutic precision. However, these tools must be transparent, explainable, and rigorously validated to ensure clinician trust and patient safety.

**Education, Training, and Workforce Capacity Building**

Widespread adoption of precision medicine requires major investment in education and professional training. Clinicians, pharmacists, nurses, and genetic counselors must be equipped with foundational knowledge in genomics, bioinformatics, and ethical interpretation of genetic data. Medical and pharmacy curricula must be updated to include precision medicine as a core component. Public education is equally important to improve genetic literacy, promote informed consent, and reduce fear or misconceptions related to genetic testing. A genomically competent workforce is essential for safe and effective clinical implementation.

Policy Development, Regulation, and Ethical Governance

Strong policy frameworks and regulatory oversight are essential for the sustainable growth of genomic medicine. Governments must establish clear regulations for genetic data protection, informed consent, data sharing, cross-border genomic research, and protection against genetic discrimination. Ethical governance mechanisms should ensure transparency, accountability, and patient rights throughout the genomic testing lifecycle. Harmonization of international genomic regulations will support global research collaboration while protecting population-level genomic sovereignty.

Ensuring Equitable Access and Health System Sustainability

Equitable access to genetic testing and precision therapies must be a central goal of future precision medicine strategies. Without deliberate affordability policies, precision genomics risks becoming limited to wealthy populations, worsening global health inequities. Governments and health systems must implement subsidy programs, public-private partnerships, and insurance coverage models to expand access across socioeconomic strata. Sustainable financing, infrastructure investment, and health system planning are necessary to ensure that the benefits of genomic medicine are distributed fairly and widely.

Clinical Applications and Case Studies

Personalized medicine has demonstrated significant clinical value across various medical specialties through the integration of genetic markers and precision therapeutic strategies. In cardiology, genetic profiling is increasingly used to guide the management of cardiovascular diseases by identifying patients' responses to anticoagulants, antihypertensive drugs, and lipid-lowering therapies. For example, variations in genes related to drug metabolism, such as CYP2C9 and VKORC1, help clinicians optimize warfarin dosing, reducing the risk of bleeding complications and improving treatment safety. Similarly, genetic testing for familial hypercholesterolemia enables early diagnosis and targeted interventions to prevent heart disease.

In neurology and psychiatric disorders, personalized medicine supports more accurate diagnosis and effective treatment planning. Genetic and molecular biomarkers are used to predict patient responses to antidepressants, antipsychotics, and antiepileptic drugs, minimizing adverse effects and treatment resistance. For instance, pharmacogenomic testing can guide the selection of antidepressants based on individual metabolic profiles, leading to improved outcomes in depression and anxiety disorders. In neurodegenerative conditions such as Alzheimer's and Parkinson's disease, genetic screening assists in identifying at-risk individuals and tailoring preventive and therapeutic strategies.

Personalized medicine has also transformed the management of rare genetic diseases, where conventional treatments are often limited. Advances in genomic sequencing enable precise identification of disease-causing mutations, facilitating early diagnosis and targeted therapies. Gene-based treatments, enzyme replacement therapies, and RNA-based drugs have shown promising results in conditions such as cystic fibrosis, spinal muscular atrophy, and Duchenne muscular dystrophy. These targeted approaches improve survival rates, enhance quality of life, and reduce disease-related complications.



Numerous success stories highlight the positive impact of precision medicine on clinical outcomes. In oncology, targeted therapies and immunotherapies guided by genetic profiling have significantly increased survival rates and reduced treatment toxicity. Inherited metabolic disorders and rare cancers have benefited from individualized treatment plans that were previously unavailable. Clinical trials and real-world studies consistently demonstrate that personalized treatment strategies lead to higher response rates, better disease control, and improved patient satisfaction. These achievements underscore the potential of precision medicine to transform healthcare delivery and promote more effective, patient-centered medical practices.

Summary:

Advances in genomic science have ushered in a new era of personalized medicine, where therapeutic strategies are informed by an individual's genetic makeup. Genetic markers such as SNPs, CNVs, and gene-expression profiles — along with polygenic risk scores — offer powerful tools for predicting disease risk, guiding drug selection and dosage, and improving overall treatment outcomes. Real-world successes in oncology, cardiology, and psychiatry demonstrate the value of precision therapeutics. However, to realize the full potential of personalized medicine globally — especially in genetically diverse and resource-constrained populations — substantial challenges must be addressed: genetic diversity and underrepresentation, infrastructural and cost barriers, ethical and privacy concerns, and lack of clinician training. We propose a conceptual framework (illustrated by graphs and tables) for integrating genetic diagnostics into routine clinical care, accompanied by recommendations for future research, capacity building, and policy development. With concerted efforts, personalized medicine can transform healthcare from a reactive model to a predictive, preventive, and participatory one — ultimately benefiting patients worldwide.

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