

Original Article

AI-Enabled Personalized Medicine and Genomic Engineering: Designing Individualized Treatments through Predictive Intelligence

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Abstract: Personalized medicine has emerged as a revolutionary approach in healthcare, aiming to tailor treatments and interventions based on individual genetic, environmental, and lifestyle factors. Traditional medical practices often rely on generalized treatment protocols that do not account for interpatient variability, which can lead to suboptimal therapeutic outcomes and adverse effects. With the advent of high-throughput genomic sequencing, multi-omics technologies, and digital health records, vast amounts of biological and clinical data are now available. Artificial intelligence (AI), particularly machine learning and deep learning models, has demonstrated significant potential in analyzing these complex datasets to generate predictive insights that guide individualized treatment strategies. In genomic engineering, AI accelerates the identification of pathogenic mutations, predicts gene-editing outcomes, and optimizes therapeutic designs, enabling precision interventions. The integration of AI with personalized medicine allows for predictive intelligence in diagnosis, prognosis, and therapy optimization, which can enhance treatment efficacy, reduce side effects, and improve overall patient outcomes. This paper explores the intersection of AI, genomic engineering, and personalized medicine, highlighting the tools and techniques used, clinical applications, ethical and legal considerations, and future directions. Through the synthesis of recent research and case studies, it underscores how AI-enabled predictive intelligence is transforming the landscape of individualized healthcare and offers a framework for designing treatments that are both precise and adaptive to patient-specific needs. The discussion also emphasizes the importance of responsible deployment, data security, and equitable access to these technologies to maximize their societal and clinical impact.

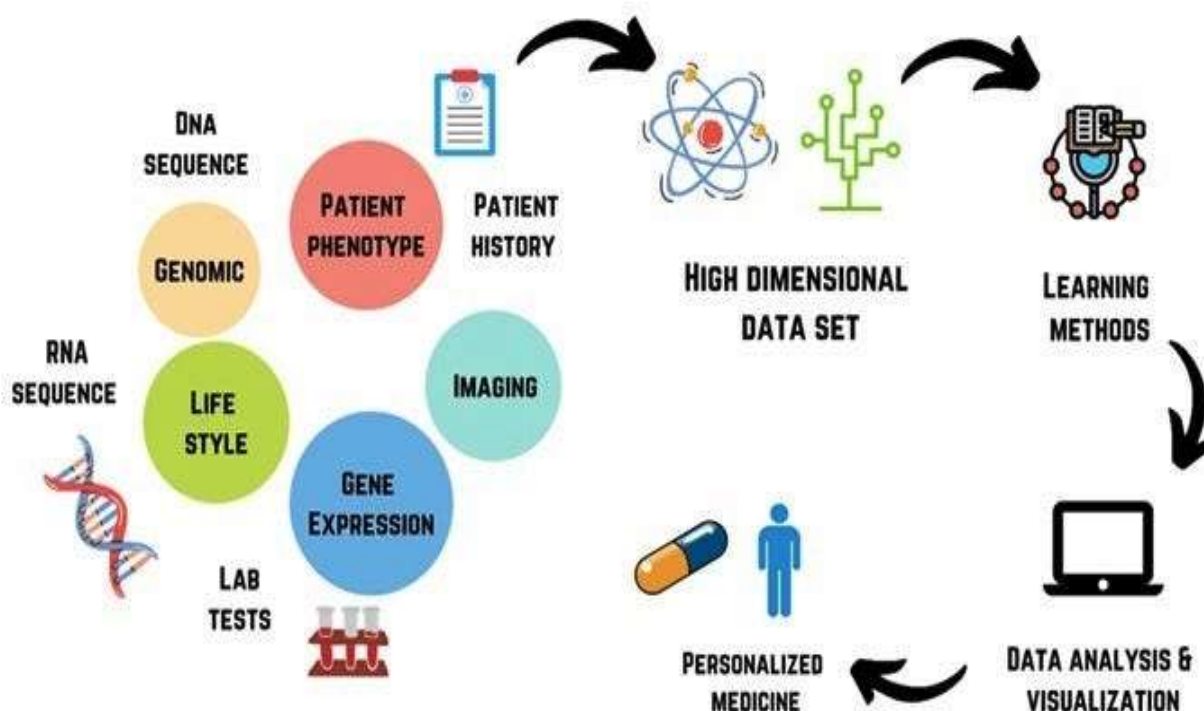
Keywords: Artificial Intelligence (AI), Personalized Medicine, Genomic Engineering, Predictive Intelligence, Precision Healthcare, AI-Augmented Decision-Making, Healthcare Analytics, Human-AI Collaboration, Clinical Decision Support, and Data-Driven Governance.

I. INTRODUCTION

Personalized medicine represents a paradigm shift in healthcare, moving away from the traditional “one-size-fits-all” approach toward strategies that account for individual patient characteristics. This approach leverages genetic, molecular, and clinical data to provide more accurate diagnoses, predict disease risk, and optimize therapeutic interventions. In recent years, the integration of artificial intelligence (AI) with personalized medicine has significantly enhanced our ability to interpret complex datasets and make predictive decisions at an unprecedented scale. AI encompasses computational methods, including machine learning, deep learning, and natural language processing, that can detect patterns in large and heterogeneous biomedical datasets.

The growing availability of genomic data, combined with high-throughput sequencing technologies, has opened new opportunities for precision medicine. Genomic engineering techniques, such as CRISPR-Cas9, enable targeted manipulation of genetic sequences to correct mutations or enhance therapeutic responses. When coupled with AI-driven predictive models, these technologies can guide individualized treatment strategies by anticipating patient responses, optimizing drug selection, and minimizing adverse effects.

Despite these advancements, challenges remain in integrating AI into clinical practice. Issues such as data privacy, model interpretability, regulatory compliance, and ethical considerations must be carefully addressed to ensure safe and effective implementation. This research paper aims to explore the convergence of AI, personalized medicine, and genomic engineering, examining how predictive intelligence can enable individualized treatment design. By analyzing existing technologies, clinical applications, and future prospects, the study provides a comprehensive overview of the transformative potential of AI-enabled healthcare solutions.



II. EVOLUTION OF PERSONALIZED MEDICINE

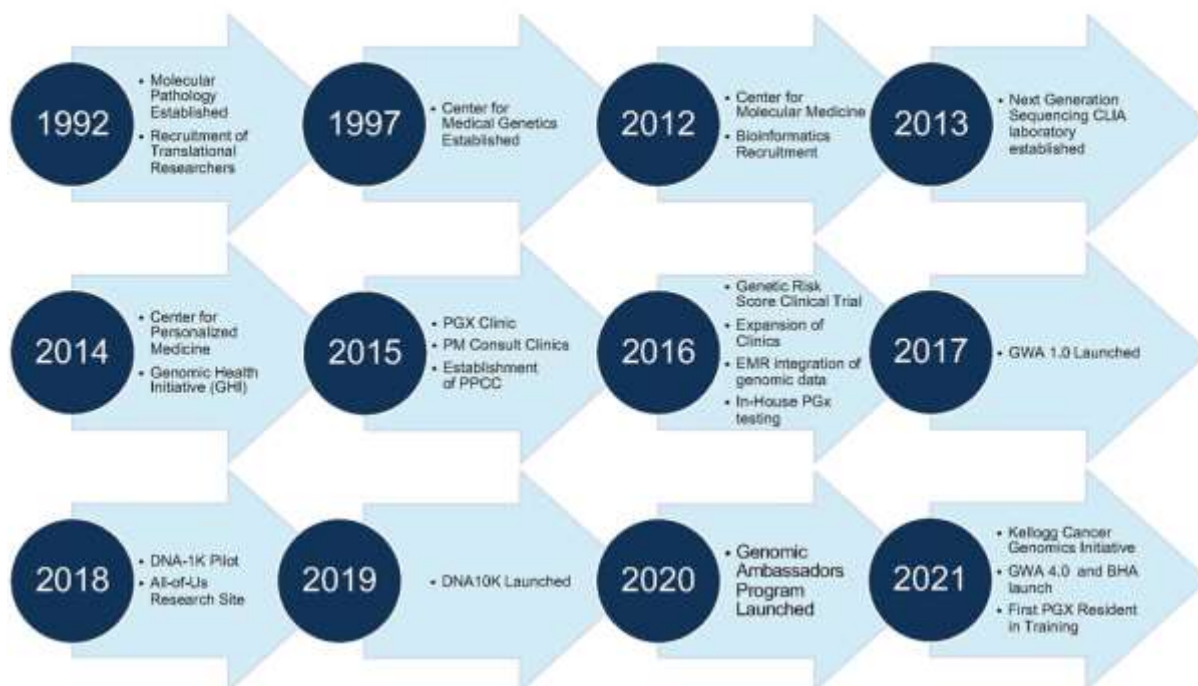
Personalized medicine has evolved from conventional, population-based approaches toward highly individualized therapeutic strategies that consider genetic, environmental, and lifestyle factors. Historically, medicine relied on generalized protocols, often resulting in variable patient outcomes due to inherent biological differences. The Human Genome Project, completed in 2003, marked a pivotal moment by providing a comprehensive map of human genetic variation, laying the foundation for precision medicine. With this knowledge, clinicians and researchers could identify disease-associated genes, understand genetic predispositions, and develop targeted interventions.

The development of biomarkers further enhanced personalized approaches. Biomarkers, such as genetic mutations, protein expression levels, and metabolic signatures, allow clinicians to stratify patients into subgroups with specific disease risks or treatment responses. Pharmacogenomics, which studies how genetic variation affects drug metabolism and efficacy, has become central to designing individualized therapies. For instance, variations in cytochrome P450 genes can predict how patients metabolize certain drugs, informing dosage adjustments to maximize efficacy and reduce adverse reactions.

Technological advances, including high-throughput sequencing, bioinformatics, and multi-omics integration, have accelerated the evolution of personalized medicine. By combining genomics, proteomics, metabolomics, and epigenomics data, researchers can construct detailed molecular profiles of patients, enabling precise diagnosis and tailored treatment planning. Personalized medicine now encompasses not only drug selection but also disease prevention strategies, lifestyle modifications, and predictive monitoring.

In recent years, the integration of artificial intelligence (AI) has transformed personalized medicine from a concept into practical clinical applications. AI algorithms can analyze complex datasets, identify hidden patterns, and generate predictive models that guide individualized interventions. These advancements have opened new possibilities for patient-centered healthcare, promising treatments that are safer, more effective, and aligned with each patient's unique biological and environmental context.

Evolution of Personalized Medicine at NorthShore



III. GENOMIC ENGINEERING: TOOLS AND TECHNIQUES

Genomic engineering, also referred to as genome editing, involves precise modification of DNA sequences to correct mutations, alter gene expression, or introduce novel genetic traits. Among the most transformative tools in this field is CRISPR-Cas9, which enables targeted editing of genomic sequences with high accuracy and efficiency. CRISPR utilizes a guide RNA to direct the Cas9 nuclease to specific DNA loci, allowing for gene knockouts, insertions, or corrections. Its simplicity, scalability, and versatility have accelerated research in functional genomics, therapeutic development, and synthetic biology.

Other genomic engineering tools include TALENs (Transcription Activator-Like Effector Nucleases) and Zinc Finger Nucleases (ZFNs), which also facilitate targeted DNA modifications. While highly precise, these tools are often more complex and less flexible compared to CRISPR, limiting their widespread adoption in clinical applications. RNA-based techniques, such as siRNA (small interfering RNA) and antisense oligonucleotides, allow transient modulation of gene expression without permanently altering the genome. These methods are particularly valuable in diseases caused by abnormal gene expression or protein accumulation.

The integration of AI has further enhanced genomic engineering by predicting off-target effects, optimizing guide RNA design, and modeling the functional impact of genetic edits. AI-driven algorithms can analyze large genomic datasets to identify candidate genes for editing, simulate therapeutic outcomes, and reduce experimental trial-and-error.

Despite its transformative potential, genomic engineering raises ethical, legal, and social concerns. Issues such as germline editing, unintended mutations, and equitable access require careful consideration. Regulatory frameworks are evolving to balance innovation with patient safety and societal responsibility. When responsibly applied, genomic engineering, in combination with AI, offers unprecedented opportunities for designing individualized treatments, preventing genetic diseases, and revolutionizing personalized medicine.

IV. AI IN HEALTHCARE: PREDICTIVE INTELLIGENCE

Artificial Intelligence (AI) has emerged as a cornerstone of modern healthcare, enabling predictive intelligence that can analyze vast and complex datasets to inform clinical decision-making. AI encompasses machine learning (ML), deep learning (DL), and natural language processing (NLP), each contributing uniquely to healthcare innovations.

A. Subtopic 1: Machine Learning in Diagnostics

Machine learning algorithms can identify patterns in imaging, genomic, and clinical data, improving diagnostic accuracy. For instance, ML models can detect early signs of diseases such as cancer or diabetic retinopathy in medical images, often outperforming traditional diagnostic methods. Predictive analytics also allows clinicians to anticipate disease progression, enabling early interventions.

B. Subtopic 2: Predictive Modeling for Disease Risk

AI-driven predictive models integrate patient genetics, lifestyle, and environmental factors to assess disease risk. These models can forecast susceptibility to chronic conditions like cardiovascular diseases or neurodegenerative disorders, supporting personalized prevention strategies.

C. Subtopic 3: AI in Drug Discovery and Development

AI accelerates drug discovery by predicting molecular interactions, optimizing compound selection, and simulating clinical trial outcomes. Deep learning models can analyze biological datasets to identify promising therapeutic targets and reduce the time and cost associated with traditional drug development pipelines.

D. Subtopic 4: Clinical Decision Support Systems (CDSS)

AI-powered CDSS provide clinicians with real-time, data-driven recommendations for treatment plans. By continuously analyzing patient data, AI systems can suggest optimal drug combinations, dosage adjustments, and monitor patient responses, minimizing adverse effects and improving treatment efficacy.

In summary, AI-enabled predictive intelligence transforms healthcare by enhancing diagnostic accuracy, optimizing treatment planning, and enabling proactive disease management. Its integration with clinical workflows and genomic insights facilitates the transition from reactive to proactive, patient-centered medicine.

V. INTEGRATING AI WITH GENOMIC DATA

The integration of AI with genomic data forms the foundation for **precision medicine**, enabling individualized treatments based on each patient's genetic profile.

A. Subtopic 1: AI-Driven Genomic Analysis

High-throughput sequencing generates massive genomic datasets that are difficult to interpret manually. AI algorithms can process this data, identifying mutations, structural variations, and epigenetic modifications associated with diseases. Machine learning models can also predict the functional impact of these genetic variants, guiding clinical decisions.

B. Subtopic 2: Patient Stratification for Precision Medicine

AI enables patient stratification by clustering individuals based on genomic, phenotypic, and environmental characteristics. This approach ensures that therapies are targeted to subpopulations most likely to benefit, improving treatment outcomes while reducing unnecessary interventions.

C. Subtopic 3: Predictive Modeling of Treatment Responses

By analyzing genomic and clinical data, AI models can predict how patients will respond to specific treatments. This capability is particularly valuable in oncology, where AI can anticipate tumor resistance patterns, guide therapy adjustments, and optimize drug selection.

D. Subtopic 4: Case Studies and Applications

Numerous studies have demonstrated AI's ability to integrate multi-omics data for personalized therapy. For example, AI models have successfully predicted gene-drug interactions in cancer patients, facilitating individualized chemotherapy regimens. In rare genetic disorders, AI-driven genomic analysis has enabled early diagnosis and the design of gene-based interventions.

The integration of AI with genomic data represents a transformative step in healthcare, bridging the gap between molecular biology and clinical practice. It allows the development of tailored treatments that are both predictive and adaptive, moving the medical paradigm toward truly personalized care.

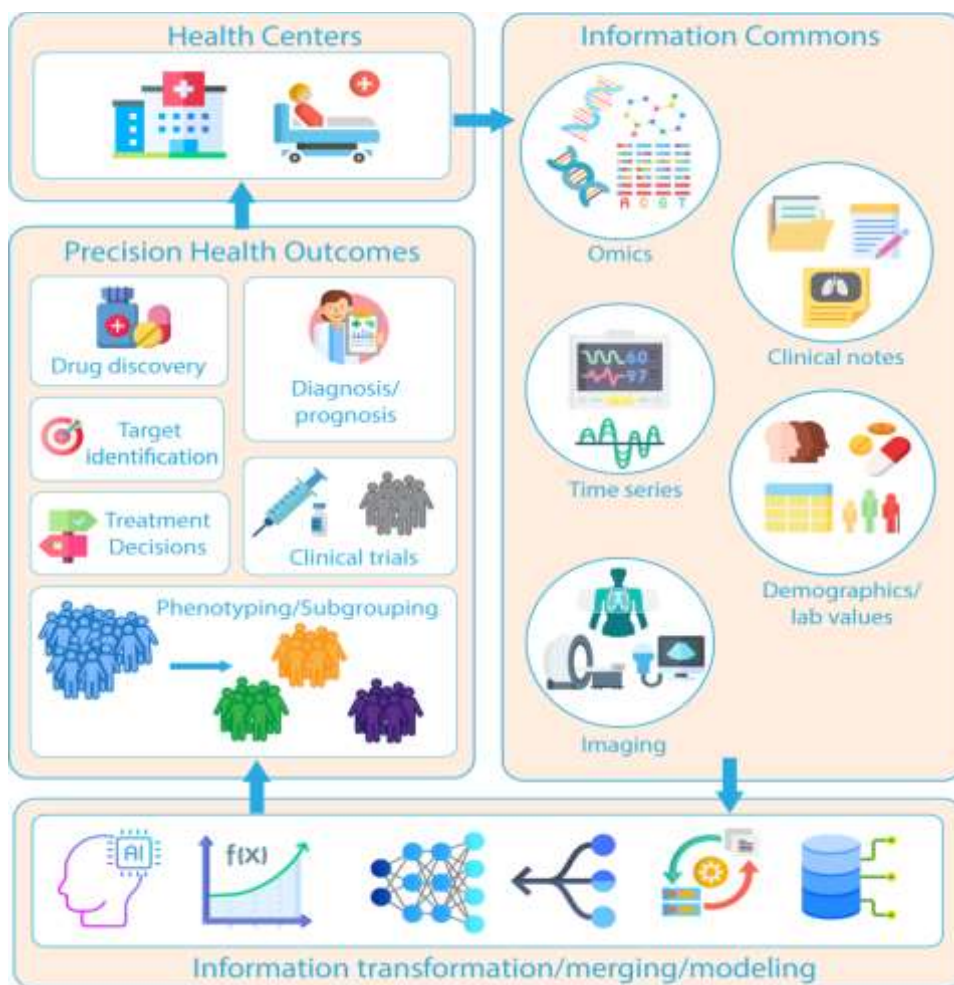
VI. DESIGNING INDIVIDUALIZED TREATMENTS

Designing individualized treatments is the central goal of personalized medicine, leveraging patient-specific data to optimize therapeutic interventions. By integrating genomic information, clinical history, environmental factors, and lifestyle patterns, healthcare providers can create highly targeted treatment plans that maximize efficacy while minimizing adverse effects. Advances in artificial intelligence (AI) play a crucial role in this process, enabling predictive models that anticipate patient responses to therapies, identify potential complications, and guide decision-making in real time.

Genomic engineering technologies, such as CRISPR-Cas9 and RNA-based therapeutics, allow for precise modifications of disease-causing genes or regulatory elements, enabling treatments tailored to a patient’s unique genetic profile. AI algorithms can simulate the effects of these interventions before administration, predicting potential off-target effects and optimizing therapeutic design. Additionally, pharmacogenomics leverages AI to personalize drug selection and dosing, ensuring that patients receive medications that are most compatible with their metabolic and genetic profiles.

Beyond drug therapy, individualized treatments extend to lifestyle and preventive interventions. AI-driven predictive analytics can identify risk factors for chronic diseases and recommend personalized exercise, nutrition, and monitoring strategies. This proactive approach not only treats existing conditions but also reduces the likelihood of disease progression or recurrence.

The integration of AI and genomic insights into treatment design represents a paradigm shift in medicine, transitioning from a reactive, population-based approach to a proactive, patient-centered model. By tailoring interventions to the biological, clinical, and behavioral characteristics of each patient, individualized treatments enhance therapeutic outcomes, improve quality of life, and reduce healthcare costs. Ultimately, this convergence of AI and personalized medicine offers the potential to transform healthcare delivery, making it more precise, predictive, and adaptive to the needs of each individual.



VII. CLINICAL APPLICATIONS AND CASE STUDIES

The application of AI-enabled personalized medicine and genomic engineering has transformed clinical practice, enabling precise diagnosis, treatment planning, and outcome prediction across various medical fields.

A. Subtopic 1: Oncology

Cancer treatment has benefited significantly from AI and genomic insights. AI algorithms can analyze tumor genomes to identify driver mutations, predict tumor behavior, and recommend targeted therapies. Personalized treatments, such as immunotherapies and precision chemotherapy regimens, are designed based on a patient's molecular profile, minimizing side effects while maximizing therapeutic efficacy. Case studies have shown that AI-assisted genomic profiling improves survival rates in patients with aggressive cancers.

Subtopic 2: Rare and Genetic Diseases

For rare genetic disorders, traditional diagnostics are often slow and inconclusive. AI-powered genomic analysis accelerates the identification of pathogenic mutations, facilitating early diagnosis and intervention. Gene-editing techniques, guided by AI predictions, have enabled precise correction of disease-causing mutations in experimental therapies. Examples include AI-assisted treatment design for inherited metabolic disorders and congenital immunodeficiencies.

Subtopic 3: Chronic Disease Management

AI and personalized medicine extend beyond genetics into chronic disease management. Predictive models can monitor patient data in real-time, detect early signs of complications, and recommend individualized treatment adjustments. For instance, AI algorithms analyze blood glucose trends in diabetic patients to optimize insulin therapy and lifestyle interventions. Similarly, cardiovascular disease management benefits from AI-driven risk prediction models that guide preventive and therapeutic strategies tailored to each patient.

Subtopic 4: Multi-Omics Integration

Integrating genomics, proteomics, and metabolomics with AI enhances precision medicine applications. Multi-omics analysis allows clinicians to understand complex disease mechanisms and design comprehensive treatment plans that address both genetic and environmental contributors to disease. Case studies in oncology and neurology demonstrate improved patient outcomes when multi-omics insights inform therapy selection.

In conclusion, the integration of AI with genomic and clinical data has transformed patient care, enabling individualized treatments that are more effective, safer, and proactive. Clinical applications across oncology, rare diseases, and chronic conditions illustrate the transformative potential of predictive intelligence in healthcare.

VIII. ETHICAL, LEGAL, AND SOCIAL IMPLICATIONS (ELSI)

The integration of AI and genomic engineering into personalized medicine brings profound ethical, legal, and social challenges that must be addressed to ensure responsible and equitable healthcare. One of the primary concerns is data privacy and security. Genomic information is inherently sensitive, and the collection, storage, and analysis of large-scale patient data pose risks of misuse, unauthorized access, and potential discrimination. Ensuring secure data management and compliance with regulations such as HIPAA and GDPR is critical for maintaining patient trust.

Ethical considerations also arise in genomic editing and AI-guided treatments. Interventions like CRISPR-Cas9 in human embryos or germline cells raise questions about consent, unintended consequences, and the potential for eugenics. Even in somatic gene therapies, the risk of off-target effects or long-term adverse outcomes must be carefully evaluated. AI systems, while powerful, are often opaque ("black boxes"), making it difficult for clinicians and patients to understand how decisions are generated. This raises issues of accountability, transparency, and informed consent in clinical practice.

Social implications include equity and access. High costs of AI-driven personalized therapies and genomic interventions may exacerbate disparities between socio-economic groups or between developed and developing regions. Ensuring fair access to these technologies is essential for global health equity. Moreover, societal attitudes toward genetic manipulation and AI in healthcare vary widely, influencing public acceptance and policy development.

Legal frameworks are evolving to regulate AI applications, genomic engineering, and patient data management. Policymakers and professional organizations must create guidelines that balance innovation with safety, efficacy, and ethical

responsibility. Interdisciplinary collaboration between clinicians, ethicists, AI experts, and legal authorities is essential to navigate these challenges.

In summary, while AI-enabled personalized medicine and genomic engineering offer unprecedented benefits, their responsible implementation requires careful attention to ethical, legal, and social dimensions, ensuring that technological advancement aligns with societal values and patient well-being.

IX. CHALLENGES AND LIMITATIONS

Despite the transformative potential of AI-enabled personalized medicine and genomic engineering, several challenges and limitations hinder its widespread adoption and clinical implementation.

A. Subtopic 1: Technical Challenges

AI models require large, high-quality datasets for training and validation. In healthcare, data is often fragmented, heterogeneous, or incomplete, which can compromise model accuracy and generalizability. Moreover, integrating multi-omics data, clinical records, and environmental information into unified predictive frameworks remains technically complex. Computational limitations and the need for advanced algorithms also pose barriers to real-time analysis and decision-making.

B. Subtopic 2: Ethical and Regulatory Constraints

Ethical concerns related to patient consent, data privacy, and genome editing may limit clinical application. Regulatory frameworks for AI-driven medicine and genomic engineering are still evolving, creating uncertainty for researchers and healthcare providers. The lack of standardized protocols for AI validation, model interpretability, and genomic editing safety can slow adoption and affect clinical trust.

C. Subtopic 3: Cost and Scalability Issues

Implementing AI-driven personalized medicine requires significant investment in infrastructure, computational resources, and specialized expertise. High costs may limit accessibility, particularly in low- and middle-income countries. Scalability of AI models to diverse populations is also a challenge, as most algorithms are trained on limited demographic datasets, potentially reducing their efficacy in broader clinical settings.

D. Subtopic 4: Clinical Integration and Adoption

Integrating AI systems into existing healthcare workflows is often challenging. Clinicians may face difficulties interpreting AI-generated recommendations or reconciling them with traditional clinical judgment. Resistance to change, lack of training, and concerns about liability can slow the adoption of AI-driven personalized medicine in practice.

In conclusion, while AI and genomic engineering offer unprecedented opportunities for individualized treatment, addressing technical, ethical, regulatory, financial, and clinical barriers is essential. Overcoming these challenges will be critical to realizing the full potential of predictive intelligence in transforming healthcare.

X. FUTURE DIRECTIONS

The future of AI-enabled personalized medicine and genomic engineering is poised to redefine healthcare by making treatments increasingly precise, predictive, and proactive. Advances in artificial intelligence, combined with the ongoing expansion of genomic and multi-omics datasets, will allow clinicians to design therapies tailored to the molecular and environmental profiles of individual patients. Emerging AI techniques, such as explainable AI and federated learning, will enhance model transparency, privacy, and generalizability, addressing key barriers to clinical adoption.

Integration of multi-omics data, including genomics, transcriptomics, proteomics, and metabolomics, will provide a comprehensive understanding of disease mechanisms. AI algorithms will be able to identify complex interactions among genes, proteins, and environmental factors, enabling highly refined predictions of disease risk and treatment response. This will facilitate the development of personalized preventive strategies, early interventions, and adaptive treatment plans.

The combination of AI with genomic engineering holds significant potential for gene and cell therapies. Predictive models can optimize gene-editing strategies, minimize off-target effects, and anticipate patient-specific responses.

Personalized immunotherapies, including engineered T-cells and CAR-T therapies, will become more accessible and effective as AI guides the selection of optimal targets and treatment protocols.

Additionally, the increasing use of wearable devices and remote health monitoring will feed real-time data into AI models, allowing continuous adaptation of personalized treatment plans. This integration of digital health and AI will enable a shift from reactive to proactive healthcare, improving patient outcomes and reducing healthcare costs.

Despite the immense promise, the future will require ongoing attention to ethical, legal, and societal implications, as well as equitable access to ensure that these innovations benefit all populations. Overall, AI-enabled predictive intelligence and genomic engineering are set to transform the landscape of personalized medicine, offering unprecedented opportunities to design treatments that are individualized, precise, and dynamic.

XI. CONCLUSION

AI-enabled personalized medicine and genomic engineering represent a transformative convergence of technology and biology, offering the potential to revolutionize healthcare by designing treatments tailored to the unique genetic, molecular, and environmental profile of each patient. By integrating artificial intelligence with high-throughput genomic and multi-omics data, clinicians can now predict disease risk, optimize therapies, and minimize adverse effects in ways that were previously unattainable. This shift from generalized treatment approaches to individualized interventions marks a significant advancement in both efficacy and patient safety.

The use of predictive intelligence allows healthcare providers to anticipate disease progression, personalize drug selection and dosing, and guide the application of cutting-edge genomic interventions such as CRISPR-Cas9 and RNA-based therapies. These capabilities are particularly impactful in areas like oncology, rare genetic disorders, and chronic disease management, where traditional approaches often fail to address patient-specific variability. Clinical case studies have demonstrated improved outcomes, earlier diagnoses, and enhanced therapeutic precision when AI-guided personalized medicine strategies are implemented.

However, realizing the full potential of these technologies requires careful attention to ethical, legal, and social implications. Issues such as data privacy, equitable access, transparency of AI models, and the responsible use of genomic engineering must be addressed to ensure safe and just application. Regulatory frameworks and interdisciplinary collaboration between clinicians, AI experts, ethicists, and policymakers are essential to facilitate the integration of these innovations into clinical practice.

In conclusion, AI-enabled predictive intelligence, combined with genomic engineering, is poised to redefine the future of healthcare. By providing highly individualized, precise, and adaptive treatments, these technologies have the potential to improve patient outcomes, reduce healthcare costs, and transform medicine into a more proactive and patient-centered discipline. The continued development, ethical implementation, and equitable distribution of these innovations will determine the extent to which personalized medicine can truly achieve its promise of tailored, effective healthcare for all.

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