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REVIEW ARTICLE

The AI revolution in personalized medicine: Clinical applications and challenges

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ABSTRACT

The integration of artificial intelligence (AI) into personalized medicine is rapidly transforming healthcare by enabling more precise, predictive, and individualized patient care. This narrative review explores the clinical applications, benefits, and limitations of AI-powered personalized medicine across multiple disciplines, including oncology, radiology, rheumatology, dermatology, ophthalmology, and pharmacology. We provide an overview of foundational AI technologies such as machine learning, deep learning, and natural language processing, highlighting their role in optimizing diagnosis, predicting treatment responses, and supporting clinical decision-making. Key examples include AI-based image interpretation in radiology, predictive models for drug metabolism in pharmacogenomics, and generative AI tools for clinical documentation and drug discovery. We also examine large-scale biomedical databases such as the UK Biobank and the Cancer Genome Atlas, which serve as critical resources for developing AI-driven models in personalized care. Although AI demonstrates substantial potential in improving healthcare delivery, challenges remain, including concerns about clinical validity, reproducibility, data bias, and the interpretability of AI models. Furthermore, ethical considerations such as data privacy, algorithmic transparency, and equitable access to AI-guided interventions are increasingly significant. This review underscores the importance of interdisciplinary collaboration and robust validation frameworks to ensure the safe, effective, and equitable integration of AI into precision medicine. By synthesizing current literature and highlighting emerging trends, we aim to inform clinicians, researchers, and policymakers on how AI can be harnessed to realize the full potential of truly personalized healthcare.

Keywords: artificial intelligence, personalized medicine, machine learning, clinical decision support, genomics, deep learning

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INTRODUCTION

Personalized Treatment

Personalized treatment is an advancing approach to healthcare that seeks to tailor medical treatment, disease prevention and health management to the unique biological, environmental and lifestyle characteristics of individual patients [1]. Doctors have been personalizing treatments for their patients for centuries. In historic Chinese medicine, for instance, remedies such as herbal mixtures, acupuncture, and carefully chose diets were adjusted for each person's unique condition [2]. Similarly, Egyptians also recognized that treatments should be adapted to individual patients rather than uniformly by emphasizing specialization by disease and body part while later advanced to patient centered care [3]. Although these approaches were based on very different theories, they show that clinicians have long tried to adjust and tailor care for the individual rather than the average patient. Personalized medicine continues today but stands out from older methods by relying on genetics, statistics, and large-scale data [2, 3].

Unlike traditional medicine, which often relies on evidence from the "average patient", precision medicine uses molecular profiles (genomes, proteomes, metabolomes, etc.), electronic health records (EHRs), environmental exposures, and social determinants of health to optimize diagnosis and optimize treatment [4].

Without this tailored approach, two patients with different genetic backgrounds or environmental influences could receive the same medication or dosage, potentially leading to ineffective treatment or harmful side effects for a patient. Precision medicine prevents this by ensuring therapeutic strategies are aligned with specific characteristics of each individual [1].

The Importance of Personal Medicine

Personalized medicine transforms healthcare by allowing doctors to move away from a one size fits all approach and instead give patients treatment that is tailored to them as individuals [1]. There are many advantages of precision medicine because the practice does not rely on a one-size-fits-all approach to healthcare. It gives healthcare providers the option of utilizing the genetic data of an individual during normal medical practice resulting in a deeper comprehension of the occurrence of diseases. This method also offers the ability to determine the most effective prevention strategies and treatments that will be used with particular groups of people, thereby enhancing the overall disease prevention, diagnosis, and treatment strategy. Moreover, precision medicine allows the incorporation of EHRs more successfully, allowing providers to more easily gain access to medical data [5].

For instance, in cancer treatment, England's National Health Service has started using a simple blood test that allows clinicians to tailor therapies based on a tumors genetic profile of individuals. This innovation speeds up diagnosis by up to 16 days, reduces unnecessary chemotherapy, and saves the system $12.8 million. In the USA, personalized medicine has already proved lifesaving: genetically engineered T-cells sent a young leukemia patient into lasting remission after other treatments failed [6]. Beyond oncology, pharmacogenomics (PGx) has helped physicians prescribe the right drug at the right dose by accounting for how an individual metabolizes medications, thereby reducing trial-and-error prescribing and preventing adverse reactions [5].

Taken together, these developments illustrate how precision medicine not only improves outcomes and spares patients from unnecessary toxicity, but also enhances early detection, strengthens drug safety, and, ultimately, makes healthcare more efficient and humane.

AI Basics, Machine Learning, Deep Learning

Artificial intelligence (AI) is a field of computer science dedicated to creating intelligent machines and programs that can perform tasks that typically would require human intelligence, but often with greater speed and accuracy [7]. A field within AI named machine learning (ML), where algorithms are trained to recognize patterns, classify data, and make predictions. Deep learning (DL), a more advanced branch of ML, uses artificial neural networks inspired by the human brain itself, to process information and improve with experience [1]. Convolutional neural networks (CNNs), which is a specialized type of DL model, are effective at interpreting images, making them valuable in many healthcare applications such as radiology and diagnostics [8].

AI is also playing an increasingly central role in personalized medicine. For example, linking EHRs with whole-genome sequencing has allowed doctors to quickly diagnose genetic disorders in infants. The convergence of EHR and whole-genome sequencing has made it possible for doctors to deliver faster and more accurate diagnoses for seriously ill infants with suspected genetic conditions. This is achieved by combining rapid whole-genome sequencing with natural language processing (NLP)-based automated phenotyping. Using NLP, AI can identify key features of a patient's condition from EHRs or medical images and link them to genetic variants. This process streamlines and improves the accuracy of diagnosing genetic disorders in infants, leading to more timely and effective care [1].

Furthermore, in rheumatology, AI tools help evaluate joint damage and predict how individual patients will respond to specific therapies by combining clinical and genomic information. To evaluate joint damage, AI is used through platforms that provide more consistent assessments. One example is an AI-based precision medicine tool designed to measure radiographic damage in patients with rheumatoid arthritis (RA). This tool uses ML models to analyze medical images and quantify the extent of joint damage. For predicting individual patient response to specific therapies, AI and especially ML models are changing how intricate health data are studied. A combination of data on clinical records, genetics, and immune system profiles provided by AI allows clinicians to see the overall picture of a patient and their health and risks. This allows creating more personalized insights regarding the autoimmune rheumatic disease patients. AI has the capability to rapidly and effectively analyze genetic markers to determine susceptibilities and probable response to treatment, and ML models can find trends in extensive datasets to inform more accurate and predictive care [9].

AI is reshaping oncology by opening new opportunities to improve cancer patient management, especially through advancements in diagnostics, detection, screening, and drug discovery [10]. AI achieves this through analyzing the large datasets, learning patterns and transferring this knowledge in enhancing decision making in the medical field. It has the ability to combine large quantities of multi-omics data with high capability computing platforms using ML and DL. It has so far had the largest effect in cancer diagnostics, where the majority of approved AI tools are currently used. Radiologists can be assisted by AI as an example, to identify nodules during computed tomography (CT), indicating suspicious regions in mammograms, and following lesions in magnetic resonance image (MRI) and CT. It can be used in pathology to identify the type of cancer, receptor status of breast cancer, as well as to detect the spread of cancer in a biopsy and lymph node. In addition to diagnostics, AI is also

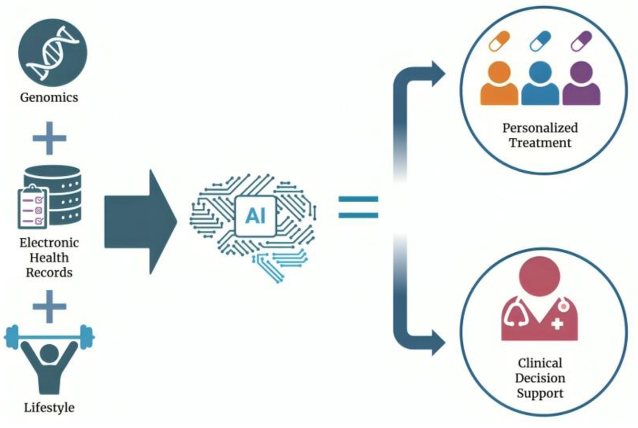

Figure 1. AI integrates data from genomics, EHRs, and lifestyle factors to enable personalized treatment and support clinical decision-making in precision medicine (Source: Authors' own elaboration)

used to research cancer genomics, examine the tumor microenvironment, evaluate biomarkers, and aid in follow-up care and drug discovery (**Figure 1**). It also has a significant role to play in radiation oncology, working on treatment planning and monitoring [11]. Together, these advances show how AI is moving beyond general applications to become a powerful tool for delivering more precise and individualized care [1, 9, 11].

Databases are a crucial for personalized medicine because they store the large amounts of information and data needed to tailor care to individual patients. The UK Biobank, for example, links genetic, clinical, and lifestyle information from over 500,000 participants [12]. Similarly, the Cancer Genome Atlas has molecularly characterized over 20,000 primary cancer samples across 33 cancer types, making it a crucial resource for understanding cancer biology [13]. Databases help create predictive models, find early warning signs of diseases, and guide treatment plans that are tailored to patients. Another database is the All of Us database, which has had over 867,000 participants, 472,000 EHRs and 611,000 bio samples. Furthermore, databases help to advance precision medicine because they allow researchers to collect, organize, and share large amounts of medical data. As more EHRs, genetic sequences, and clinical trial results are stored in large, accessible databases, researchers gain access to broader and more diverse information. This wealth of data makes it possible to identify new patterns, risk factors, and treatment responses across different patient populations. With stronger evidence from larger datasets, more scientific research can be conducted, ultimately leading to deeper and better insights and more effective personalized treatments tailored to each patient.

CLINICAL APPLICATION AREAS

Usage of AI in Oncology Treatments

AI is a key facilitator of precision medicine in oncology, a field that aims to provide personalized treatment plans by comprehensively learning the individual features of the tumor of each patient [14]. AI, especially ML and DL is essential to process and analyze the massive amount of big data produced in cancer research and clinical practice [7]. This encompasses multi-omics data such as genomics, transcriptomics and proteomics and multi-mode data such as radiomics, digital pathological images and electronic medical records [15]. AI can extract concealed patterns, important information, and relevant knowledge of these high-dimensional, heterogeneous datasets, enabling clinicians to gain a comprehensive understanding of tumors, discover new biomarkers, and develop new discoveries that are essential in personalized cancer treatment, which ultimately improves clinical outcomes. This ability fills the gap between complex omics data and clinical use to offer a detailed perspective of tumor alterations in genes, proteins, and cancer cell phenotypes to create targeted approaches [15].

Precision oncology using AI can be applied in the whole range of cancer management, including early detection and post-treatment [11]. In diagnosis and screening, AI has a significant positive impact on the rate of lesion detection, the ability to distinguish between true and false disease progression, and the correct staging and classification of tumors through the analysis of digital pathological images and medical imaging data [11, 15]. AI can be used in treatment planning and prediction to consider different treatment options and suggest the most appropriate course of action to individual patients [11]. This involves the ability to predict drug efficacy, therapeutic responses, and probability of recurrence or metastasis using combined omics and quantitative imaging data, which in turn guides the design of targeted drugs and tailored approaches to therapies such as chemotherapy and radiotherapy. Moreover, AI-based multi-omics integration is essential to uncover the complex biological processes, elucidate causal links in complex diseases, and discover dynamic diagnostic and prognostic biomarkers to provide accurate cancer care.

Finally, AI contributes to the development of individualized treatment regimens that increase patient viability, maximize the chances of survival, and improve the overall quality of life by forecasting the results and informing the post-treatment care, differentiating between actual progression and radiation necrosis, and optimizing radiotherapy doses and targets [15].

Radiology

Radiology forms a foundation of precision medicine, and imaging methods, including X-rays, MRI, and positron emission tomography scans, are used to give detailed internal images to improve the accuracy of diagnosis and inform individualized therapy [16, 17]. As AI is integrated, radiology is moving even further, with AI enhancing image interpretation, data analysis, and pattern recognition. These functions enable the earlier identification, real-time tracking, and tailoring of the treatment plans, which makes interventions more efficient and less invasive [17]. Key performance indicators (KPIs) are needed to measure and enhance radiological practices in a systematic way, particularly through the incorporation of AI [16].

KPIs will also make sure that the technological progress is aligned with the precision medicine objectives by monitoring the diagnostic accuracy, efficiency, and patient satisfaction. AI can also be used to create more advanced KPIs by revealing the latent trends in large volumes of data, which can be used to optimize workflows, anticipate results, and offer patient-centered care to the radiology departments [16, 17].

Rheumatology

Precision medicine, with the help of AI, will make a significant contribution to rheumatology by transforming the old approach of one-size-fits-all into the personalized approaches to a particular patient [9]. This development is motivated by AI that applies ML and DL to categorize diseases and forecast the results based on the analysis of large and complex data [9, 18]. AI can help clinicians to have a complete picture of the health of a patient by combining various sources of data, such as EHRs, genetics, and immunology. As an example, ML models can detect high-risk patients who require rheumatology testing as early as five years before conventional methods by using longitudinal EHR data (EHRs collected for individual patients over an extended period of time). AI algorithms have been shown to be highly accurate in diagnosing rheumatic diseases like RA using lab data, distinguishing RA and osteoarthritis on hand radiographs, and identifying sacroiliitis on X-rays and CT scans in diagnostics [18]. Moreover, AI applications are superior at disease progression, treatment response, and complications. There are models that are created to help predict the response of methotrexate in patients with RA, predict hospitalization in patients with systemic lupus erythematosus (SLE) and predict mortality in patients with systemic sclerosis. These AI-powered precision medicine platforms may optimize treatment plans, select patients to receive suitable treatments, and finally transform patient care and outcomes by analyzing clinical, genomic, and imaging data [9, 18, 19].

In addition to diagnosis and prognosis, generative AI is becoming an effective tool that can streamline the whole research and clinical process in rheumatology, which will further promote precision medicine [18]. Large language models (LLMs) can generate new content and help make complex decisions, which is known as generative AI. These models have been shown to be able to summarize information, help in writing clinical notes and serve as clinical decision support systems. Research indicates that LLMs can be highly accurate in diagnosing rheumatic diseases, and in some cases, as accurate as rheumatologists, and can give accurate and high-quality responses to patient queries about drugs and diseases such as SLE. AI is also speeding up drug discovery through prediction of protein structures, drug targets, and in clinical trial design. Regarding the research process itself, AI tools may assist in brainstorming ideas, automated literature reviews, data analysis, and manuscript preparation. AI can streamline research by developing so-called digital twins or artificial control arms to conduct clinical trials. The integration of the analytical capabilities of discriminative AI with the capabilities of generative AI to synthesize data and assist with clinical workflow will help medical breakthroughs and innovations to accelerate and reach a new stage of personalized patient care in the field of rheumatology [18, 19].

Dermatology

AI and precision medicine are two advancing fields transforming dermatology by improving diagnostic accuracy, personalizing treatment, and enhancing clinical workflows [20, 21]. ML and CNNs are the most effective AI models in the image-based diagnosis of skin cancer, the most prevalent type of cancer globally [20, 21]. Research has shown that AI algorithms can identify skin lesions using dermoscopic images with the same accuracy as clinicians [21]. This is essential since early detection of melanoma, a fatal skin cancer, has a tremendous effect on survival [21]. The use of AI is also applicable to other imaging modalities such as automated total body scanning to localize lesions and monitor the progression of these lesions over time, which is useful in risk stratification [20].

Teledermatology and smartphone apps, which can enhance access to care in patients, help in triaging suspicious lesions, and raise patient awareness, are also being integrated with AI [21]. Moreover, AI has the potential to complement sequential digital dermoscopy, which can identify subtle lesion changes over time, to allow clinicians to diagnose melanoma earlier than by themselves. The interaction between humans and AI has provided better results and this implies that AI is not to be used as a substitute but rather as an aid to supplement the knowledge of a clinician [21].

In dermatology, precision medicine entails the application of skin lesion, blood or tumor genomic profile biomarkers to inform therapy of both inflammatory dermatoses and cutaneous malignancies [20, 22]. In the case of inflammatory diseases such as psoriasis, a machine-learning-based test, which uses transcriptome of skin patches, can predict how a patient will respond to various biologic therapies, including IL-17 or TNF-alpha blockers [20, 22]. This will enable the clinicians to avoid the trial and error method and choose the most effective treatment early on which could result in huge cost savings [20]. The same accuracy method might be used in atopic dermatitis and prurigo nodularis. Precision medicine is already established in the field of oncology. In case of advanced basal cell carcinoma, treatments such as vismodegib are directed at the mutations in the Hedgehog signaling pathway [20]. In the case of melanoma, gene expression profile (GEP) tests are used in diagnosis, prognosis, and metastatic risk stratification, which is essential information used to make decisions on surveillance and management. Likewise, GEP tests of cutaneous squamous cell carcinoma are able to detect high-risk patients who are likely to develop metastasis, which can be used to make decisions regarding follow-up and subsequent treatment [20]. This personalized care will provide more efficient and effective care that will enhance patient outcomes in a broad range of skin conditions [20, 22].

Ophthalmology

AI is rapidly transforming ophthalmology, a field particularly suited for its application due to a reliance on digital imaging like optical coherence tomography (OCT) and visual field testing [23, 24]. Tools are being used to screen, diagnose and treat several vision threatening diseases. Indicatively, in age-related macular degeneration (AMD), which is one of the leading causes of central vision loss, AI is able to identify important features in OCT images such as drusen, predict visual acuity, and identify the necessity of anti-VEGF treatment [24]. Even the retina specialists have been outperformed by DeepSeeNet, an AI system, in the classification of the severity of AMD based on fundus images [23]. Similarly, in glaucoma, which is the second most common cause of vision loss in the world, DL algorithms have been more accurate than experts in identifying disease progression using OCT scans and fundus images [24]. In the case of diabetic retinopathy (DR), the leading cause of vision loss in diabetic patients, the Federal Drug Association in 2018 approved the IDx-DR system that automatically examines patients with fundus images [24]. Surgical planning, outcome prediction, and screening of retinopathy of prematurity in children are also under investigation using AI. In general, these applications are aimed at enhancing prompt detection and prevention of vision loss, particularly in underserved or rural regions [23, 24].

Precision medicine has developed in ophthalmology including genetic testing of uveal melanoma and gene therapy of inherited retinal diseases such as Luxturna [25, 26]. But it is yet to be used extensively on more general ailments such as AMD or DR. The absence of companion diagnostics to pair patients with molecular treatments, including anti-VEGF injections, is one of the key challenges [26]. These injections are done to millions of patients annually, yet a third of them do not respond favorably, which puts them at risk of paying and losing money. Vitreous humor liquid biopsies are a safe, molecule-rich site that could be used to determine which patients would respond to such treatments [26]. Nonetheless, the unwillingness to carry out these biopsies has slowed down the advancement. The creation of standardized processes and equipment in vitreous biopsies may increase individualized therapies and speed up novel therapies. Finally, AI coupled with precision medicine has the potential to provide more effective and individualized care in ophthalmology, resulting in improved outcomes and bringing the field to the same level as other medical fields [25, 26].

Pharmacology

AI and ML are transforming pharmacological research, the whole spectrum of drug discovery into personalized medicine in clinical practice [27-29]. The first major effect of AI can be seen in the drug discovery and design stage, which is a long and expensive process with a low success rate [27, 29]. The first step, the analysis of 3D protein structures, has been radically transformed by software such as AlphaFold, which has been able to predict the structure of 98.5% of human proteins, and serves as a starting point in drug design, a process that would have required decades of experimental work alone [29]. Based on this structural information, AI can be used to speed up virtual screening to find promising drug compounds in large chemical libraries [27]. Both structure-based (predicting binding affinity) and ligand-based (similarities between known active molecules) methods are complemented by AI models such as deep neural networks that can effectively pre-screen candidates. Moreover, AI is important in reducing end stage failures by forecasting the possible toxicity of a compound, including cardiotoxicity and hepatotoxicity, with high accuracy at an early developmental stage. Drug repositioning is also possible with the help of AI, whereby existing drugs are proposed to new treatment applications by comparing disease GEPs with drug databases, which is especially useful in rare diseases and in finding new treatment options in diseases such as colorectal cancer and Alzheimer's disease [27, 29]. The AI-driven de novo drug design extends the chemical space by producing completely novel molecules with models such as recurrent neural networks and generative adversarial networks.

AI is not only used in the laboratory, but also in clinical pharmacology, where it is a foundation of precision medicine-a strategy aimed at personalizing treatment considering the differences in genes, environment, and lifestyle [28]. Data integration and analytics play a significant role in this paradigm shift, where ML algorithms are used to process large volumes of data, such as EHRs and omics technologies, to provide the five rights: the right drug, patient, time, dose, and route. One of them is PGx, where the therapy is matched to the genetic profile of a patient to maximize its effectiveness and reduce side effects. As an example, AI neural network models are able to predict the activity of the CYP2D6 enzyme, which metabolizes approximately 30 percent of most commonly used drugs, with much greater accuracy than traditional approaches. In clinical practice, AI can be used to optimize drug therapy regimens with a narrow therapeutic index (e.g., therapeutic drug monitoring) based on algorithms to recreate patient pharmacokinetic profiles and prescribe personalized doses

[28, 29]. Another way AI is used to optimize clinical trials is to process EHR data to enhance patient recruitment and track participants in real-time with wearables [28, 29]. The idea of digital twins, or virtual patient profiles, enables silico clinical trials to simulate the effects of treatment on individual people prior to their use in practice. Another field of AI is NLP, which extracts unstructured data in EHRs to obtain real-world evidence on clinical outcomes, drug interactions, and adverse reactions to create a feedback loop that constantly optimizes therapeutic approaches. Despite the obstacles, including data quality, the black-box nature of certain models, and integration into hospital workflows, AI capability to work with complex data is clearly moving pharmacology to the next stage of more effective and personalized patient care [27-29].

Limitations

Despite the rapid advances in personalized medicine and AI-driven healthcare, important limitations remain regarding clinical validity and reliability. Clinical validity is the extent to which a test or a model predicts a clinical outcome. Numerous genomic and biomarker-based tools are promising in research but may not be validated in large and heterogeneous populations of patients. As an example, genetic variations that are applied to prescribe drugs tend to vary in frequency and impact based on ancestry. When predictive models are trained with small datasets, they might not be predictive and therefore lead to inequities and less trust in clinical decisions. Likewise, early cancer or autoimmune biomarkers can identify abnormalities, but not all of them can result in actionable disease outcomes, which results in overdiagnosis or unnecessary interventions. Furthermore, AI often has cases of "hallucinations", where it can generate information that is false misleading. This can often lead to problematic results and data.

Reliability involves consistency and reproducibility of results in real-world clinical settings. Personalized treatments often rely on complex laboratory techniques (e.g., whole-genome sequencing, transcriptomics, and multi-omics integration) that can vary between institutions and labs. Variability in sample collection, data quality, or computational pipelines may cause inconsistent outcomes. Moreover, AI-driven systems are susceptible to "black-box" decision-making, where clinicians cannot fully interpret how a recommendation was generated. This raises questions about accountability, reproducibility, and integration into standard clinical workflows.

Taken together, these issues highlight that while personalized medicine has immense potential, its current limitations in validity, reproducibility, generalizability, and transparency must be addressed before it can become fully reliable in everyday healthcare.

CONCLUSION

The convergence of AI and personalized medicine marks a paradigm shift in clinical practice by facilitating tailored therapeutic approaches that account for the unique genetic, environmental, and lifestyle factors of individual patients. Across diverse medical fields—from oncology to dermatology—AI has demonstrated the ability to improve diagnostic accuracy, streamline treatment planning, and optimize patient outcomes. However, despite these advances, significant challenges remain, including variability in data quality, lack of transparency in AI-driven decisions, and the need for standardized validation protocols. Moreover, ethical concerns such as data privacy, algorithmic bias, and equitable access must be systematically addressed to ensure responsible integration of AI into routine care. Going forward, a multidisciplinary strategy that combines robust clinical evidence, technological innovation, and ethical oversight will be essential to realize the transformative potential of AI in precision medicine. Continued investment in data infrastructure, regulatory frameworks, and clinician education will play a crucial role in shaping the future of personalized healthcare.

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AI statement: The authors stated that no generative AI or AI-based tools were used in the writing, editing, analysis, or preparation of this manuscript.

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