Digital Chinese Medicine

Artificial intelligence in personalized cardiology treatment

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ABSTRACT

Cardiovascular diseases are the leading cause of death, requiring innovative approaches for prevention, diagnosis, and treatment. Personalized medicine customizes interventions according to individual characteristics, with artificial intelligence (AI) playing a key role in analyzing complex data to improve diagnostic accuracy, predict outcomes, and optimize therapies. AI can identify patterns in imaging and biomarkers, facilitating the earlier detection of medical conditions. Wearable devices and health applications facilitate continuous monitoring and personalized care. Emerging fields such as digital Chinese medicine offer additional perspectives by integrating traditional diagnostic principles with modern digital tools, contributing to holistic and individualized cardiovascular care. This study examines the advancements and challenges in personalized cardiovascular medicine, highlighting the need to address issues such as data privacy, algorithmic bias, and accessibility to promote the equitable application of personalized medicine.

1 Introduction

Cardiovascular diseases (CVD) remain a principal cause of morbidity and mortality on a global scale, affecting millions of lives with significant health repercussions [1]. Despite advancements in therapeutic strategies, conventional treatment protocols often rely on standardized approaches, which may inadequately address the intricate physiological, genetic, and lifestyle differences unique to each patient. Such one-size-fits-all methodologies overlook the nuanced interplay of these factors, potentially limiting their effectiveness and compromising patient outcomes [2-5].

The increasing acknowledgment of these limitations has catalyzed a paradigm shift toward precision medicine, a framework that seeks to tailor medical care to the individual characteristics of each patient [6]. The growing field of artificial intelligence (AI) is at the heart of this transformation. Rapid advancements in AI technologies, including machine learning (ML), deep learning (DL), and natural language processing (NLP), offer unprecedented opportunities to harness vast, complex datasets, ranging from electronic health records (EHRs) and imaging studies to genomic profiles and real-time health indicators (Table 1) [7-9]. These innovations facilitate a granular understanding of patient-specific factors, paving the way for personalized treatment strategies that significantly enhance clinical outcomes [10, 11].

The integration of AI into cardiology has transformed risk stratification, diagnosis, and treatment [12]. Advanced

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Table 1 Glossary of medical terms and concepts

Term	Definition	Clinical relevance
AI	A field of computer science focused on creating systems capable of performing tasks that typically require human intelligence	Enhances clinical decision-making, diagnostics, and personalized treatment in cardiology
ML	A subset of AI involving algorithms that improve performance by learning from data	Enables predictive modeling for cardiovascular events and outcomes
DL	A type of ML utilizing neural networks with multiple layers to analyze complex data patterns	Powers advanced diagnostics like AI-ECG analysis and image-based disease detection
NLP	A branch of AI that interprets and processes human language	Facilitates insights from unstructured data like electronic health records and clinical notes
AUC	A graph depicting the performance of a classification model across thresholds	Used to measure the accuracy of AI diagnostic tools in cardiology
ECG	A test that records the heart's electrical activity	AI-ECG enhances diagnostic precision for arrhythmias, myocardial infarction, and other cardiac conditions
Dilated cardiomyopathy	A condition where the heart's ability to pump blood is reduced due to an enlarged, weakened left ventricle	AI identifies genetic variants like *TTN* to inform personalized management strategies
SCD	Unexpected death due to heart-related causes within a short time frame	AI-based models improve risk prediction, enabling timely interventions
TTN	A protein encoded by the *TTN* gene, mutations of which are common in dilated cardiomyopathy	AI integrates genetic data to refine diagnosis and treatment
Wearable devices	Portable health monitors that track physiological parameters like heart rate and activity	AI leverages wearable data for real-time monitoring and early detection of complications
Telemedicine	Remote delivery of healthcare services using technology	AI-supported telehealth improves access and efficiency in cardiovascular care, particularly in remote areas
MACE	A composite endpoint of heart attack, stroke, or cardiovascular death	AI tools predict MACE to tailor preventive and therapeutic measures
CTIschaemia	AI-based imaging analysis to detect ischemic changes in coronary arteries	Provides enhanced prognostic information for suspected coronary artery disease (CAD)
Deep reinforcement learning	A type of AI that uses trial and error to optimize decisions based on outcomes	Facilitates drug dosing and therapeutic optimization in complex clinical scenarios
Digital Chinese medicine	A modern approach that integrates traditional Chinese medicine (TCM) principles with digital technologies, such as AI, to analyze clinical data and develop personalized treatment protocols	Digital Chinese medicine leverages AI to refine diagnostic accuracy and tailor treatments, particularly for cardiovascular diseases, by incorporating large-scale clinical data from diverse populations, enhancing precision medicine globally

AUC, area under the curve. ECG, electrocardiogram. SCD, sudden cardiac death. *TTN*, *Titin*. MACE, major adverse cardiovascular events. CTIschaemia, computed tomography ischemia.

algorithms analyze genetic predispositions, behavioral patterns, and physiological markers with precision, enabling early detection and personalized management. For instance, AI-driven ECG analysis improves diagnostic accuracy for conditions like hypertrophic cardiomyopathy (HCM) and ST-elevation myocardial infarction (STEMI) while predicting SCD and guiding risk management strategies [13, 14].

Beyond diagnostics, AI facilitates individualized treatment by integrating diverse patient data to optimize medication regimens, customize lifestyle interventions, and support real-time monitoring through wearable devices. These innovations improve therapeutic outcomes and address disparities by overcoming barriers such as geographic and resource limitations.

The potential of AI to advance personalized care is exemplified by digital Chinese medicine [15, 16]. Through digitizing extensive clinical data from diverse populations,

digital Chinese medicine leverages AI to refine diagnostic accuracy and develop tailored treatment protocols [16]. This illustrates how large-scale digital platforms can expand access to precision medicine and inform global healthcare advancements.

This review explores AI's transformative role in cardiology, focusing on its applications in predictive analytics, therapeutic optimization, and patient monitoring. It emphasizes the need for equitable implementation to ensure that these benefits are accessible, thereby fostering a more inclusive and effective healthcare landscape.

2 The emergence of AI in cardiology

The evolving landscape of cardiology has embraced a considerable influx of innovative AI technologies, including ML, DL, and NLP. These advanced methodologies

leverage extensive datasets, such as EHR, imaging studies, and genomic information, to extract novel patterns and insights that were previously elusive [17, 18].

2.1 ML algorithms

ML algorithms are pivotal in effectively processing and analyzing intricate datasets, allowing healthcare professionals to predict cardiovascular incidents and overall patient outcomes with heightened accuracy [19]. DL models utilizing ECG tracings have shown promising results in diagnosing various conditions, with areas under the receiver operating characteristic (ROC) curve (AUC) exceeding 90% for some diagnoses like atrioventricular block (AVB), HCM, mitral valve stenosis (MS), and STEMI [14] (Table 2). These predictive models, ranging from logistic regression to advanced neural network frameworks, have exhibited potential roles in accurately identifying individuals at significant risk for severe cardiovascular events, such as heart attacks [20].

Table 2 Overview of clinical implications of AI in cardiology: key applications and representative advancements

AI application	Clinical implication
ML algorithms in ECG interpretation	Improves diagnostic accuracy for conditions like AVB, HCM, MS, and STEMI
Predictive analytics for risk stratification	Enhances individualized risk assessments, early intervention for high-risk patients
Integration of patient-specific data	Synthesizes diverse data sources for comprehensive cardiovascular health profiling
Telemedicine and remote monitoring	Enables timely interventions through real-time patient monitoring
Digital Chinese medicine	AI tools like PowerAI-CVD enhance cardiovascular risk prediction in Chinese populations, while AI-based systems improve disease diagnosis in TCM

This table provides a high-level summary based on cited literature; specific data points mentioned in the text are drawn from individual studies and are not directly reported in this table.

2.2 Predictive analytics

AI-driven predictive analytics employs historical patient data to project future health trajectories [21, 22]. Tools and models influenced by AI, like the Framingham Heart Study and the atherosclerotic CVD (ASCVD) risk calculator, offer refined risk assessments tailored to individual profiles. In a study involving a large cohort of SCD cases and controls, a DL model achieved an AUC of 0.889 for SCD detection, significantly surpassing the conventional model's AUC of 0.712 [13]. These findings suggest that AI-powered ECG analysis could enhance risk stratification and potentially enable earlier interventions for individuals at high risk of SCD.

Additionally, genetic testing in dilated cardiomyopathy has identified a range of causative genes, with *TTN* being the most commonly implicated, accounting for 15% – 20% of cases [23] (Table 2). Other genes associated with dilated cardiomyopathy, such as lamin A/C (*LMNA*), sodium voltage-gated channel alpha subunit 5 (*SCN5A*), RNA binding motif protein 20 (*RBM20*), and filamin C (*FLNC*), exhibit distinct phenotypic expressions and varying degrees of penetrance, underscoring the genetic heterogeneity of this condition [23]. While genetic testing offers valuable insights, its predictive capabilities can vary. Therefore, clinicians should integrate genetic data with traditional diagnostic tools for better risk stratification.

By integrating genetic, biochemical, and lifestyle information, these personalized risk models equip clinicians with valuable insights to develop preventive strategies that align precisely with each patient's needs.

2.3 Integration of patient-specific data

AI empowers the seamless consolidation of diverse patient-specific data sources, including diagnostic imaging results, data from wearable health devices, and genomic profiles [24, 25]. In a study evaluating the prognostic value of an AI-guided quantitative computed tomography ischemia algorithm (AI-QCTischaemia) in patients with suspected CAD, an abnormal AI-QCTischaemia result was associated with a two-fold increased adjusted rate of long-term death, myocardial infarction (MI), or unstable angina pectoris [26] (Table 2). Additionally, the use of AI-guided single-lead ECG analysis in a wearable ring demonstrated promising results for STEMI detection, achieving an accuracy of 91.2%, sensitivity of 89.6%, and specificity of 92.9% [27]. However, another study based on the Health Information National Trends Survey (HINTS) revealed that only 18% of USA adults with established CVD and 26% at risk for CVD reported using wearable devices, compared to 29% of the general population. Furthermore, the study found that older age, lower educational attainment, and lower household income were associated with lower odds of wearable device use [28]. These findings underscore the potential for wearable devices to exacerbate disparities in cardiovascular health outcomes unless strategies are implemented to ensure equitable adoption. By synthesizing this diverse information, AI provides a comprehensive picture of a patient's cardiovascular health [24].

This underscores the transformative potential of AI in enhancing diagnostic accuracy and risk stratification,

particularly in identifying individuals at risk who may benefit from early intervention. However, the successful integration of AI in cardiology hinges on addressing challenges related to data accessibility and ensuring equitable implementation to avoid exacerbating existing healthcare disparities.

2.4 Telemedicine and remote monitoring

The rise of telehealth technologies, encouraged by AI, has permitted ongoing patient monitoring and robust data collection [29]. A recent study revealed that AI-ECG-assisted triage significantly reduced door-to-balloon time for STEMI patients in the emergency department (82.0 min vs. 96.0 min, P = 0.002) and ECG-to-balloon time for both emergency and inpatient cases (78.0 min vs. 83.6 min, P = 0.011) [30]. Additionally, the AI-ECG system exhibited a high positive predictive value of 89.5% and a negative predictive value of 99.9% for STEMI detection (Table 2).

AI tools can efficiently analyze data remotely, identifying early indicators of complications and enabling prompt interventions when necessary [31]. A deep learning-based multi-label interpretable diagnostic model, trained on a large-scale Chinese ECG dataset, achieved an impressive F1 score of 83.51% and an average AUC score of 0.977 for six common arrhythmias. Notably, the model's performance on a concealed dataset exceeded that of cardiologists, underscoring the potential of AI to enhance the accuracy and efficiency of ECG interpretation [32]. This capability is instrumental in managing chronic cardiovascular conditions like heart failure, where ongoing monitoring can significantly decrease hospitalization rates and enhance patient safety [29, 31].

These advancements in AI-driven ECG analysis and remote monitoring expedite critical interventions like those in STEMI cases, and empower healthcare providers to manage chronic conditions proactively, ultimately improving patient outcomes and reducing the burden on healthcare systems. Integrating AI in telemedicine and remote patient monitoring systems can revolutionize cardiovascular care delivery, particularly in underserved or remote areas where access to specialized care may be limited [15].

2.5 Digital Chinese medicine in cardiology

Population-specific cardiovascular risk prediction tools are essential for addressing variations in demographics, clinical profiles, and risk factors. A recent study developed PowerAI-CVD [15], the first AI-based tool specifically designed for Chinese patients, to predict MACE, including myocardial infarction, stroke, heart failure, and cardiovascular mortality (Table 1).

This tool demonstrated substantial predictive accuracy, outperforming traditional methods and providing personalized risk assessments by incorporating variables

such as pre-existing conditions, medications, and laboratory markers. The findings highlight that risk factors and predictors may vary significantly between populations, necessitating the development of tailored models to optimize outcomes [15]. Additionally, a recent study developed an AI-based diagnostic system for TCM, capable of diagnosing 187 diseases based on EHR notes [16]. Using NLP and an integrated learning model, the system achieved high diagnostic accuracy of 80.5% for the top-1 predictions, 91.6% for the top-3, and 94.2% for the top-5 [16]. This approach demonstrates the potential of AI to improve TCM diagnosis through tailored tools, highlighting the need for population-specific AI models in medicine (Table 2).

An extensive nationwide study in China developed AI models for screening and diagnosing 11 types of CVD using cardiac magnetic resonance imaging (CMR) in 9 719 individuals. The AI models demonstrated high accuracy (AUC: 0.988 for screening, 0.991 for diagnosis) and outperformed cardiologists in diagnosing pulmonary arterial hypertension [33].

In conclusion, personalized AI tools for Chinese populations demonstrate significant potential in improving cardiovascular risk prediction and diagnosis, offering more accurate and tailored solutions compared with traditional methods. These advancements emphasize the need for population-specific models to optimize healthcare outcomes.

3 AI applications in personalized treatment planning

3.1 Drug selection and dosing

AI has been revolutionizing pharmacology and advancing precision medicine across multiple disciplines. By evaluating patient characteristics and genetic variants, AI can assist in pinpointing the most suitable therapeutics and dosages for distinct patients [34, 35].

A proof-of-concept study utilizing AI identified proarrhythmic patterns in a population of 127 electrophysiological profiles, with G_{K1} being the most significant current for classifying proarrhythmicity [36]. The study also highlighted the varying effects of antiarrhythmic drugs based on the electrophysiological profile, revealing a higher tendency for fibrillation in dilated atrial tissue (87 profiles) compared with normal-sized tissue (80 profiles) [36]. These findings suggest that AI algorithms can aid in identifying patient-specific electrophysiological characteristics and predicting responses to antiarrhythmic drugs, thereby paving the way for more personalized treatment of atrial fibrillation. These capabilities not only minimize adverse drug reactions, but also amplify therapeutic effectiveness [35].

A deep reinforcement learning model designed for optimizing warfarin dosing in patients with atrial

fibrillation revealed a substantial positive correlation between algorithm-consistent dosing and time in therapeutic international normalization ratio (INR) range, with an R^2 value of 0.56. Moreover, each 10% increase in algorithm-consistent dosing was independently associated with a 6.78% improvement in time in therapeutic range (TTR) and an 11% reduction in the composite clinical outcome of stroke, systemic embolism, or major hemorrhage [37].

The potential of AI in optimizing drug selection and dosing extends beyond efficacy, promising significant economic benefits by minimizing adverse drug reactions and hospitalizations. Furthermore, by customizing treatments to align with individual patient profiles, AI can help reduce health disparities and improve access to effective therapies, particularly for underserved populations. However, the successful implementation of AI in this domain requires careful consideration of ethical implications and potential biases to ensure equitable, and patient-centered care.

3.2 Lifestyle and behavioral interventions

AI systems excel at recommending individualized lifestyle modifications rooted in comprehensive health data analysis [38, 39]. An AI-mediated, real-time, personalized lifestyle intervention program has significantly improved cardiovascular risk factors, including an average weight loss of 6.5% and a 10.9% reduction in HbA1c levels. The program also led to notable decreases in blood pressure (systolic about 1%, diastolic about 5.9%) and triglycerides (about 30%) [40]. These results highlight the potential of AI-driven lifestyle interventions to address chronic diseases and promote cardiovascular health effectively.

A survey-based assessment involving 67 experts in obesity medicine and clinical nutrition revealed that AI-generated weight-loss diet plans were often indistinguishable from those utilized at major tertiary medical centers. The AI-generated personalized diet plans received scores above neutral in all evaluation categories, including effectiveness, balance, comprehensiveness, flexibility, and applicability [41]. These findings indicate that AI has the potential to significantly contribute to personalized weight-centric care.

By assessing activity levels, dietary choices, and biometric information obtained through wearables, AI can deliver personalized recommendations that promote compliance with healthier lifestyle practices, such as increased physical activity or dietary changes. These interventions are essential for the effective management of cardiovascular health [38, 39].

3.3 Device management and imaging techniques

In the realm of implantable devices, such as pacemakers and defibrillators and cardiac imaging interpretations,

AI significantly enhances monitoring capabilities [42, 43]. Sophisticated algorithms can monitor device performance in real time, evaluate patient responses, predict potential complications, and guide timely medical interventions [42, 44]. A study utilizing deep learning methods to analyze T-wave/R-wave (T/R) ratios in patients with adult congenital heart disease (ACHD) found a significant difference in the mean and median T/R values compared with a control group ($P < 0.001$). The study also observed a significant difference in the T/R standard deviation between the two groups ($P = 0.04$), suggesting greater T/R fluctuation in ACHD patients [45]. These findings underscore the potential of AI to improve subcutaneous implantable cardioverter defibrillator (S-ICD) eligibility screening in ACHD patients by providing a more nuanced characterization of the T/R ratio, which may help reduce the incidence of inappropriate shocks.

A blinded, randomized, and non-inferiority clinical trial demonstrated that the initial assessment of left ventricular ejection fraction (LVEF) by AI was non-inferior to assessment by sonographers, with a significantly lower proportion of studies requiring substantial change (16.8% vs. 27.2%, $P < 0.001$). The AI-guided workflow also saved time for sonographers and cardiologists, further highlighting its potential to improve efficiency in echocardiography interpretation [43]. These findings suggest that AI can play a valuable role in assisting with the initial assessment of cardiac function, potentially leading to faster and more accurate diagnoses.

AI is revolutionizing device management and imaging techniques in cardiology. It enables real-time monitoring of implantable devices, predicts potential complications, and optimizes device settings for enhanced performance. Moreover, AI aids in the accurate assessment of cardiac function, resulting in faster diagnoses and improved efficiency in echocardiography interpretation.

3.4 Challenges and ethical considerations

Despite the promising prospects of AI in refining personalized cardiology treatment planning, hurdles remain, including data privacy issues, the necessity for algorithmic standardization, and concerns regarding potential biases inherent in AI systems [46-48].

Data privacy issues arise from the extensive use of sensitive patient information, with potential breaches and inadequate informed consent posing ethical and legal dilemmas. Algorithmic standardization is critical to ensure consistency, reproducibility, and seamless integration into clinical workflows, yet the lack of universal guidelines hinders widespread adoption. Perhaps most concerning is algorithmic bias, particularly regarding race, ethnicity, gender, and socioeconomic status. AI models trained on non-representative datasets may perpetuate disparities, leading to inaccurate risk assessments and inequitable

care for underrepresented groups. For instance, cardio-vascular risk prediction tools developed using predominantly populations of European descent may underestimate risks for individuals from other racial and ethnic backgrounds, potentially contributing to health disparities. Addressing these challenges requires diverse and inclusive datasets, bias detection mechanisms, robust regulatory oversight, and interdisciplinary collaboration to ensure AI tools are fair, transparent, and equitable. Without proactive mitigation, these issues risk undermining trust in AI and widening existing healthcare disparities, ultimately limiting the transformative potential of AI in personalized cardiology.

A study examining patient perspectives on the ethical use of AI in SCD risk assessment and ICD implantation decisions involved semi-structured interviews with 24 patients in Germany and the Netherlands. The study revealed that while patients recognized the potential of AI to improve healthcare, they also expressed concerns about the loss of the "human touch" and emphasized the importance of physician involvement in evaluating AI recommendations and ensuring patient-centered care [43].

The integration of AI within digital medicine for diverse populations, especially those characterized by extensive and diverse demographics like in China, necessitates the consideration of ethical issues, including algorithmic biases in interpreting culturally specific health paradigms [49]. Transparent methodologies and inter disciplinary collaboration are essential to ensure AI respects both scientific principles and cultural considerations [50, 51].

These findings underscore the need for ethical guidelines and policies that address not only the technical aspects of AI integration but also the preservation of the human element in clinical practice. Ethical concerns regarding informed consent and the appropriate role of clinicians vis-à-vis AI-assisted decision-making must be navigated meticulously [52]. It is crucial to ensure that AI tools augment rather than replace clinical expertise, thereby preserving the integrity and nuances of patient-centered care.

4 Future directions

As we look to the future, the role of AI in personalizing treatment planning in cardiology is poised to expand significantly [10]. Ongoing advancements in AI methodologies, combined with an expanding repository of patient data, will further enhance predictive capabilities and the precision of treatment strategies. Furthermore, fostering collaboration among healthcare professionals, data analysts, and regulatory agencies will be vital in establishing best practices, guidelines, and ethical frameworks for the integration of AI technologies into clinical settings.

5 Conclusion

In summary, AI holds transformative potential for personalized treatment planning within the domain of cardiology, offering actionable insights derived from intricate patient-specific data. By harnessing advanced computational techniques, AI enables a paradigm shift from generalized treatment approaches towards more precise, individualized care strategies that aim to optimize health outcomes for patients suffering from CVD. As the field continues to evolve, the incorporation of AI is expected to not only enhance clinical decision-making but also strengthen patient engagement, ultimately fostering a more holistic approach to cardiovascular health management. The future trajectory of cardiology is likely to be shaped by the convergence of technology and personalized medicine, with AI serving as a cornerstone for this evolving landscape.

Competing interests

The authors declare no conflict of interest.

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人工智能在个性化心脏病治疗中的应用

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【摘要】心血管疾病是导致死亡的重要原因，亟需创新方法以改进其预防与诊疗。个性化医疗通过根据个体特征定制干预措施，在这一领域中，人工智能（AI）通过分析复杂数据在提高诊断准确性、预测预后及优化治疗方案发挥了关键作用。AI 能够识别影像学与生物标志物中的模式，从而促进疾病的早期检测。可穿戴设备与健康应用程序促进了持续监测与个体化护理。数字中医药等新兴领域通过将传统诊断原理与现代数字工具相结合，提供了额外的视角，有助于整体和个性化心血管护理。本研究探讨了个性化心血管医疗的前沿进展与当前挑战，强调需解决数据隐私、算法偏倚及可及性等问题，以促进个性化医疗的公平应用。

【关键词】人工智能；机器学习；个性化医疗；心脏病；患者预后；风险分层；数字中医药；伦理考量