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Advancements and applications of Artificial Intelligence in cardiology: Current trends and future prospects

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ABSTRACT

Using Artificial intelligence technologies in cardiology has witnessed rapid advancements across various domains, fostering innovation and reshaping clinical practices. The study aims to provide a comprehensive overview of these AI-driven advancements and their implications for enhancing cardiovascular healthcare. A systematic approach was adopted to conduct an extensive review of scholarly articles and peer-reviewed literature focusing on the application of AI in cardiology. Databases including PubMed/MEDLINE, ScienceDirect, IEEE Xplore, and Web of Science were systematically searched. Articles were screened following a defined selection criteria. These articles' synthesis highlighted AI's diverse applications in cardiology, including but not limited to diagnostic innovations, precision medicine, remote monitoring technologies, drug discovery, and clinical decision support systems. The review shows the significant role of AI in reshaping cardiovascular medicine by revolutionising diagnostics, treatment strategies, and patient care. The diverse applications of AI in cardiology showcased in this study reflect the transformative potential of these technologies. However, challenges such as algorithm accuracy, interoperability, and integration into clinical workflows persist. AI's continued advancements and strategic integration in cardiology promise to deliver more personalised, efficient, and effective cardiovascular care, ultimately improving patient outcomes and shaping the future of cardiology practice.

1. Introduction

Cardiovascular diseases (CVDs) remain a leading cause of morbidity and mortality globally, representing a significant health challenge in the 21st century [1]. Despite significant advancements in medical science and healthcare, the prevalence of CVDs continues to rise, necessitating innovative strategies for prevention, early detection, precise diagnosis, personalised treatment, and effective management [2]. Artificial intelligence (AI) integration has emerged as a transformative force in cardiology, offering unprecedented opportunities to revolutionise how cardiovascular diseases are approached, diagnosed, and treated [3,4]. AI encompasses a spectrum of technologies, including machine learning, deep learning, natural language processing, and predictive analytics, which have rapidly evolved to augment human decision-making processes and address critical challenges in cardiovascular care [5].

Historically, the diagnosis and treatment of cardiovascular conditions have relied heavily on conventional approaches, which often face limitations in precision, early detection, and individualised treatment strategies [6]. However, the emergence of AI technologies has ushered in a new era characterised by data-driven insights, predictive algorithms, and personalised medicine tailored to the unique characteristics of each patient [7,8]. The application of AI in cardiology leverages vast amounts of data generated through various sources such as electronic health records (EHRs), imaging studies, genetic profiles, wearable

Abbreviations: AI, Artificial Intelligence; CVDs, Cardiovascular Diseases; ECG, Electrocardiogram; EHR, Electronic Health Records; HF, Heart Failure; CAD, Coronary Artery Disease; AF, Atrial Fibrillation; PAH, Pulmonary Artery Hypertension; CT, Computed Tomography; MRI, Magnetic Resonance Imaging; CDSS, Clinical Decision Support Systems; IBM, International Business Machines Corporation.

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devices, and continuous monitoring systems [9,10]. These datasets, often characterised by their complexity and volume, are the foundation for developing AI-driven algorithms that can learn, adapt, and derive meaningful insights from the data [10].

Integrating AI into cardiology aims to enhance clinical decision-making, improve diagnostic accuracy, optimise treatment strategies, and improve patient outcomes [11]. AI-driven solutions have the potential to not only augment the capabilities of healthcare professionals but also streamline processes, reduce diagnostic errors, and enable proactive interventions, thus leading to more effective and personalised patient care [12,13]. The rapid evolution and adoption of AI technologies in cardiology have led to remarkable advancements across multiple domains. Diagnostic algorithms can now analyse electrocardiograms (ECGs), echocardiograms, cardiac imaging, and other diagnostic modalities with heightened accuracy, aiding in the early detection and characterisation of cardiovascular pathologies [14]. Furthermore, AI facilitates the development of personalised treatment plans by integrating diverse patient data, including genetic profiles, lifestyle factors, and imaging results, thereby enabling tailored therapeutic interventions [4,15]. The convergence of AI with remote monitoring technologies and wearable devices has expanded the horizons of cardiac healthcare, enabling continuous real-time monitoring outside clinical settings [16]. These innovations offer the potential for timely detection of anomalies, early intervention, and personalised management of chronic cardiovascular conditions, enhancing patient engagement and improving long-term outcomes.

As AI-driven technologies advance, they promise to reshape clinical practice and research endeavours within cardiology. From drug discovery and development to risk stratification, predictive analytics, and the evolution of clinical decision support systems, AI drives a paradigm shift in cardiovascular healthcare, emphasising precision, efficiency, and improved patient-centric care. However, alongside the promising advancements, integrating AI in cardiology brings multifaceted challenges. Ethical considerations, algorithmic biases, data security, regulatory compliance, and the effective integration of AI tools into existing healthcare infrastructures remain pivotal areas that demand careful deliberation and strategic solutions [17]. This comprehensive review aims to underscore the pivotal significance and novelty of integrating artificial intelligence (AI) in cardiology while delineating its multifaceted impact on reshaping cardiovascular healthcare.

2. Methods

A systematic approach was employed to comprehensively review scholarly articles, research papers, and peer-reviewed journals relevant to the application of artificial intelligence (AI) in cardiology. Databases were systematically searched, including PubMed/MEDLINE, ScienceDirect, IEEE Xplore, and Web of Science. The search was conducted using combinations of keywords such as "artificial intelligence," "machine learning," "cardiology," "cardiovascular diseases," "AI in diagnostics," "precision medicine," "remote monitoring," and "drug discovery." Boolean operators (AND, OR) were utilised to refine the search queries and ensure the inclusivity of relevant literature.

Articles selected for review encompassed studies published between 2000 and December 2023 that focused explicitly on the application of AI in various aspects of cardiology, including but not limited to diagnostics, treatment, precision medicine, remote monitoring, and drug discovery. Peer-reviewed articles, research papers, systematic reviews, meta-analyses, and clinical trials were considered for inclusion. Non-English articles, editorials, letters, conference abstracts, and studies not specifically related to cardiology or AI applications were excluded.

Pertinent information from the included articles was extracted, encompassing study objectives, methodologies, AI techniques utilised, specific applications in cardiology, and key findings. The synthesised data were categorised into thematic areas corresponding to the diverse applications of AI in cardiology, including diagnostic innovations, precision medicine, remote monitoring, drug discovery, and challenges of clinical decision support systems. This approach allowed for a comprehensive analysis and synthesis of the selected literature.

3. Results

For this review, an extensive database search yielded a total of 236 potentially relevant articles. Duplicates were removed using Zotero software, resulting in 84 unique articles. Titles and abstracts of the remaining articles were independently screened by two reviewers to assess their relevance based on predetermined inclusion and exclusion criteria. Following this initial screening, 52 articles were deemed potentially relevant and selected for full-text review. The full texts of these selected articles were thoroughly reviewed to determine final inclusion, resulting in a total of 37 articles included in the review (See Fig. 1). Any discrepancies in article selection were resolved through consensus between the two reviewers.

Table 1 provides a detailed overview of the identification, screening, and selection process of articles across four databases: PubMed/MEDLINE, Sciencedirect, IEEE Xplore, and Web of Science.

4. Discussion

4.1. Diagnostic innovations in cardiology using AI

Artificial intelligence (AI) has ushered in a new era of diagnostic capabilities in cardiology, significantly enhancing the accuracy, efficiency, and early detection of various cardiovascular diseases [3]. AI-driven diagnostic tools have revolutionised the interpretation of electrocardiograms (ECGs), echocardiograms, cardiac imaging, and other diagnostic modalities, improving patient outcomes and more precise clinical decision-making across various cardiac conditions [18–20].

AI-powered algorithms have shown remarkable advancements in the analysis of ECGs, enabling rapid and accurate interpretation of these crucial tests [21]. Specific conditions, such as arrhythmias (like atrial fibrillation) and conduction abnormalities, can be accurately detected by AI systems, aiding in timely diagnosis and appropriate management strategies [22]. For instance, companies like AliveCor have developed AI-based algorithms capable of detecting atrial fibrillation through smartphone-based ECG recordings, facilitating early intervention and reducing the risk of stroke [23]. AI has significantly impacted echocardiographic imaging, enabling more precise and detailed analysis of cardiac structures and function [24]. For example, AI algorithms developed by Ultromics use echocardiographic data to assess left ventricular function and predict coronary artery disease [25]. These algorithms aid clinicians by automating time-consuming tasks and providing accurate assessments, contributing to more informed diagnostic

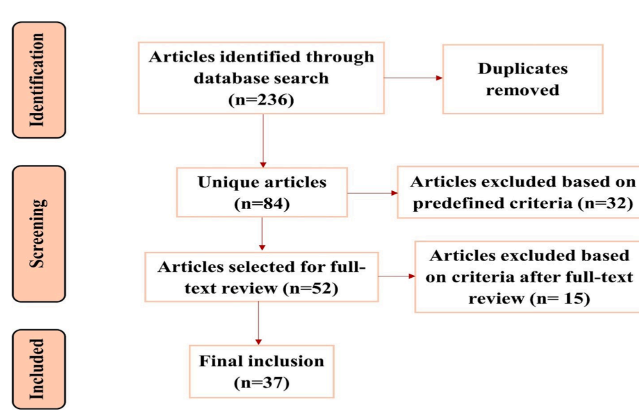

Fig. 1. PRISMA flowchart for selection of articles.

Table 1
Identification, Screening, and Selection of Articles across Databases.

Database	Identification	Screening (Initial and final)	Selection
PubMed/ MEDLINE	102	27	19
ScienceDirect	76	13	11
IEEE Xplore	37	7	4
Web of Science	21	5	3
Total	236	52	37

decisions [26].

AI-driven innovations in cardiac imaging, including MRI and CT scans, have enhanced the accuracy of detecting and characterising various cardiac pathologies [27]. For instance, AI-powered software by Arterys leverages machine learning to analyse cardiac MRI scans, providing automated measurements of cardiac function and aiding in detecting abnormalities such as myocardial infarctions and cardiac tumours [28]. AI-based tools are crucial in early diagnosis of diseases like pulmonary artery hypertension (PAH) [29]. Researchers have developed AI algorithms that analyse cardiac MRI images to detect and predict PAH progression [30]. These tools assist in identifying subtle changes in pulmonary circulation and cardiac function, allowing for early intervention and improved patient management.

AI has also demonstrated significant promise in detecting and characterising coronary artery disease [31]. Machine learning models are trained on extensive datasets of cardiac CT angiography images to identify and quantify coronary artery stenosis [32] accurately. Companies like HeartFlow have developed non-invasive AI-based tools that create personalised 3D models of coronary arteries to assess the functional significance of blockages, aiding in treatment planning and decision-making for patients with CAD [33]. AI-based predictive models utilise various data sources, including patient records and imaging data, to predict heart failure exacerbations [34]. These models assist clinicians in identifying high-risk individuals, optimising treatment strategies, and improving patient outcomes by enabling proactive interventions and personalised management plans [35].

On the other hand, Artificial intelligence (AI) holds promise in predicting patient readmission in heart failure management, offering valuable insights for proactive intervention and personalized care planning [36]. Recent studies have demonstrated the efficacy of AI-driven predictive models in forecasting heart failure exacerbations and identifying patients at high risk of readmission [37,38]. For instance, studies have reported developments of AI algorithms such as CART model that analyzed electronic health record data to predict heart failure readmissions with high accuracy, outperforming traditional risk prediction models [39,40]. Similarly, machine learning techniques to

Table 2
AI in Diagnostic Innovations.

Disease Area	Specific Condition	AI Tool Description	Benefits	Challenges	Examples
Coronary Artery Disease (CAD) [42, 43]	Atherosclerosis detection:	Deep learning algorithms trained on X-ray angiograms and CT scans identify plaque build-up and stenosis levels in coronary arteries.	Early detection, improved risk stratification, personalized treatment planning.	High computational cost, data bias risks, potential for false positives.	Zebra Medical's "Coronary CTA" tool, GE Healthcare's "Edison AI for Cardiology"
	Ischemia prediction:	Machine learning models analyze ECGs, stress tests, and other data to predict risk of future coronary events.	Risk stratification, targeted preventive measures, resource allocation.	Limited data on outcomes, potential for overfitting, ethical considerations of risk prediction.	Phillips' "Tachycardia & Bradycardia Detection", BioSig Technologies' "HeartCloud AI"
Heart Failure [41,44]	Left ventricular ejection fraction (LVEF) estimation:	Deep learning models analyze echocardiograms to measure LVEF, a key indicator of heart function, with high accuracy.	Non-invasive assessment, earlier diagnosis, monitoring therapy response.	Image quality variations, dependence on operator expertise, limited data on diverse populations.	EchoPixel, Caption Health "AI LVEF"
	Prognosis prediction:	AI models analyze clinical data (symptoms, lab tests, imaging) to predict risk of adverse events and long-term outcomes.	Personalized care plans, optimized resource allocation, improved patient engagement.	Data quality issues, bias in training data, difficulty capturing complex patient factors.	Cleerly's "CardioML", Ultromics' "CorticalAI"
Arrhythmias [45,46]	Atrial fibrillation (AF) detection:	AI algorithms analyze ECGs to detect AF episodes with high sensitivity and specificity, even in short recordings.	Early diagnosis, improved anticoagulation management, stroke prevention.	ECG noise interference, rare arrhythmia detection limitations, data privacy concerns.	AliveCor's "KardiaMobile", BioIntelliSense's "BSN Medical ECG Patch"
	Cardiovascular implantable electronic device (CIED) analysis:	AI models analyze CIED data (pacemakers, defibrillators) to identify arrhythmias, device malfunctions, and predict clinical events.	Early detection of complications, remote monitoring, optimized device settings.	Device compatibility issues, cybersecurity concerns, limited data on newer CIED models.	Evolent Health's "IntellyCare", St. Jude Medical's "Merlin.NET Patient Management System"
Cardiomyopathies [47,48]	Hypertrophic cardiomyopathy (HCM) screening:	AI algorithms analyze ECGs and echocardiograms to identify subtle features suggestive of HCM, a common inherited heart muscle disease.	Early diagnosis, family screening, improved disease management.	Overlapping features with other conditions, dependence on image quality, limited data on diverse populations.	Sonoware's "SonoCalc", Qventus Medical's "CardioCloud HCM"
	Myocarditis diagnosis:	Machine learning models analyze MRI scans to differentiate myocarditis from other inflammatory conditions with high accuracy.	Improved diagnostic accuracy, avoiding unnecessary invasive procedures, personalized treatment approaches.	Myocardial edema heterogeneity, image noise challenges, limited data on rare subtypes of myocarditis.	HeartVista's "CardioMRI AI", Arterys' "Voyager AI"
Congenital Heart Defects (CHDs) [49,50]	Prenatal CHD detection:	Deep learning algorithms analyze fetal echocardiograms to identify structural abnormalities with high accuracy, enabling early intervention.	Improved prenatal counseling, optimized delivery planning, neonatal surgery preparation.	Image quality limitations, technical challenges of fetal imaging, ethical considerations of prenatal testing.	GE Healthcare's "Volpara Fetal", Philips' "FetalVue AI"
	Postnatal CHD diagnosis and management:	AI models analyze cardiac MRI and CT scans to differentiate complex CHD types and guide surgical planning.	Improved diagnostic accuracy, patient-specific surgical planning, optimized resource allocation.	Data scarcity for rare CHDs, complex anatomy variations, challenges in integrating diverse imaging modalities.	Siemens Healthineers' "Syngo.via", HeartVista's "CardioMRI AI for Congenital Heart Disease"

identify clinical predictors of heart failure readmission, enabling clinicians to stratify patients based on their risk profile and tailor preventive interventions accordingly [38,41]. By harnessing the power of AI to analyze diverse patient data, including clinical parameters, biomarkers, and imaging results, clinicians can proactively identify individuals at heightened risk of readmission, implement targeted interventions, and optimize treatment strategies to reduce the burden of heart failure readmissions and improve patient outcomes. Table 2 below highlights how AI is utilised across a spectrum of cardiovascular diseases, showcasing specific applications and tools used in diagnostics.

4.2. Precision medicine and treatment personalization

Precision medicine in cardiology represents a pivotal shift towards personalised treatment strategies, harnessing individual patient characteristics, genetic nuances, and disease-specific details [51]. At the heart of this transformative approach lies artificial intelligence (AI), which plays a fundamental role in deciphering extensive and varied datasets to craft personalised therapeutic plans, predict treatment responses, and optimise strategies for diverse cardiovascular conditions [52]. Within precision medicine in cardiology, several specific diseases illustrate the utilization of novel AI tools [53].

AI-Powered Risk Prediction Models pioneered by entities like Verily and Duke University, AI algorithms assimilate patient-specific data, incorporating genetic profiles, medical histories, and imaging outcomes to forecast the risk of CAD development and subsequent adverse cardiovascular events [54]. These predictive models effectively identify high-risk individuals, enabling proactive interventions for prevention. Siemens Healthineers has developed AI-driven predictive models that analyse a range of patient data, encompassing biomarkers, imaging results, and clinical histories, to anticipate exacerbations in heart failure [55]. These models aid clinicians in devising personalised care plans and refining treatment strategies tailored to HF patients. AI algorithms, employed by companies such as Myogenes and Corvidia Therapeutics, interpret genetic data to forecast individual responses to specific antiarrhythmic medications utilised in managing AF [56]. This tailored approach assists clinicians in selecting the most effective treatment options based on the patient's genetic makeup.

Tools like Cardiogram and Omron Healthcare's HeartGuide leverage AI capabilities to interpret continuous blood pressure monitoring data [57]. These systems offer personalised recommendations for managing hypertension, facilitating proactive interventions and lifestyle modifications based on individualised data. Platforms such as Zebra Medical Vision employ advanced AI algorithms to analyse imaging data and metabolic profiles [58]. This comprehensive assessment assists in early detection and personalised strategies for mitigating cardiometabolic risk factors.

AI-powered tools like Fabric Genomics and Genoox aid clinicians in interpreting genetic variants linked to inherited cardiomyopathies [59]. These tools provide critical insights into genetic mutations, guiding personalised treatment decisions and family counselling. Pharmacogenomics and AI Analysis: Genuity Science employs AI algorithms to analyse pharmacogenomic data, predicting individual responses to cardiovascular medications [60]. This approach facilitates the selection of the most effective and safe treatment options for patients.

These examples underscore the transformative potential of AI-driven precision medicine tools in reshaping cardiovascular care. By integrating diverse patient data, AI empowers clinicians to craft tailored treatment plans, considering individual variations. This personalised approach leads to more effective interventions, reduced adverse effects, and improved patient outcomes [61]. As AI technologies evolve, the scope for precision treatment strategies in cardiology is expected to broaden, offering even greater precision in managing cardiovascular diseases. Table 3 outlines specific AI applications in precision medicine for various cardiovascular diseases, and examples of AI tools or technologies utilised in treatment personalisation.

Table 3
AI applications in precision medicine, and the novel AI tools used for treatment personalization.

Cardiovascular Disease	Precision Medicine AI Application	Specific AI Tool/Technology
Coronary Artery Disease (CAD)	Risk Prediction and Treatment Guidance	– Verily's AI models for CAD risk prediction using genetic, clinical, and lifestyle data [62]. – Duke Cardiovascular Research Institute's AI platform aiding in treatment decision-making based on patient-specific factors and imaging data [63].
Heart Failure (HF)	Prognostic and Therapeutic Optimization	– Siemens Healthineers' AI models forecasting HF exacerbations and recommending tailored interventions leveraging patient biomarkers, imaging, and clinical history [64]. – PhysIQ's AI analytics monitoring HF patients, adjusting therapies for personalized care [65].
Atrial Fibrillation (AF)	Genomic Analysis for Drug Response Prediction	– Corvidia Therapeutics' AI algorithms assessing genetic markers to guide treatment decisions in AF patients [66].
Hypertension Management	Continuous Monitoring and Adaptive Therapy	– Cardiogram's AI-powered continuous blood pressure monitoring, providing real-time data analysis and personalized lifestyle recommendations [67]. – Omron Healthcare's HeartGuide utilizing AI to recommend personalized therapy based on continuous blood pressure data [68].
Cardiometabolic Risk Assessment	Integrated Analysis for Risk Profiling	– Zebra Medical Vision's AI platform combining imaging, genetic, and clinical data to assess cardiometabolic risk factors, aiding in early intervention strategies [69].
Inherited Cardiomyopathies	Genetic Variant Interpretation and Familial Screening	– Genoox's AI-driven genomic analysis for identifying genetic predispositions and guiding familial screening for cardiomyopathies [70].
Drug Response Prediction	Pharmacogenomics and Treatment Optimization	– Tempus' AI-powered analysis of genetic and clinical data for precise medication selection and dosing in cardiovascular treatments [71].
Stroke Prediction and Prevention	Risk Assessment and Intervention Guidance	– RapidAI's AI platform aiding in early stroke detection and providing personalized treatment recommendations [72].

4.3. Remote monitoring and wearable technology

Remote monitoring and wearable technology represent a dynamic frontier in modern cardiology, revolutionising how patients' health is tracked, managed, and intervened upon [73]. These innovative tools, coupled with advancements in artificial intelligence (AI), have transformed the landscape of cardiovascular care, enabling continuous monitoring and real-time data collection outside traditional clinical settings [74]. Wearable devices, ranging from smartwatches and fitness trackers to advanced biosensors, have empowered individuals to actively monitor their health parameters, including heart rate, blood pressure, activity levels, and even electrocardiograms (ECGs) [75]. These devices collect a wealth of physiological data, providing a comprehensive overview of an individual's cardiovascular health continuously.

Artificial intelligence plays a crucial role in harnessing the vast streams of data generated by wearable devices [76]. AI algorithms analyse this continuous influx of data, identifying patterns, anomalies, and potential indicators of cardiac irregularities. For instance, algorithms can detect subtle changes in heart rhythm patterns, signalling potential arrhythmias or abnormalities, prompting timely intervention or alerting healthcare providers [77]. Moreover, remote monitoring systems equipped with AI capabilities facilitate seamless real-time data transmission from wearable devices to healthcare providers [78]. This enables clinicians to monitor patients' health statuses remotely, assess trends in physiological parameters, and intervene proactively when deviations or concerning patterns arise.

In cardiology, these technological advancements have significant implications. For patients with chronic cardiovascular conditions such as heart failure or arrhythmias, remote monitoring coupled with wearable devices offers a lifeline [73]. It allows for continuous surveillance of vital signs, enabling early detection of worsening conditions, timely intervention, and preventing hospital readmissions. Furthermore, remote monitoring and wearable technology foster a more patient-centred approach to healthcare. Patients experience increased engagement and empowerment in managing their health, fostering a sense of autonomy and active involvement in their treatment plans. This shift towards patient-centric care promotes better adherence to treatment regimens and encourages lifestyle modifications, ultimately improving overall cardiovascular outcomes. As wearable technology continues to evolve and AI algorithms become more sophisticated, the potential for remote monitoring to play an integral role in preventive cardiology and chronic disease management grows exponentially [79]. The amalgamation of these technologies holds the promise of monitoring, predicting, preventing, and managing cardiovascular diseases in a more personalised and proactive manner, revolutionising the way cardiology is practised and enhancing patient care.

Despite the significant advancements, remote monitoring and wearable technology in modern cardiology come with notable limitations. One critical limitation lies in the variability and accuracy of data obtained from wearable devices, which may be affected by factors such as device placement, signal noise, and user compliance [75]. Studies have highlighted discrepancies between wearable-derived data and gold-standard measurements, raising concerns about the reliability of data for clinical decision-making [79,80]. Moreover, the lack of standardization in data collection protocols and device interoperability poses challenges for data integration and analysis across different platforms. Additionally, issues related to data privacy, security, and regulatory compliance remain prominent, raising ethical and legal concerns regarding patient confidentiality and data protection. Furthermore, disparities in access to wearable technology and digital literacy may exacerbate existing healthcare inequities, limiting the widespread adoption and utility of remote monitoring solutions [81]. Addressing these limitations requires concerted efforts to standardize protocols, improve data accuracy and reliability, enhance privacy and security measures, and promote equitable access to wearable technology, ensuring its safe and effective integration into modern cardiology practice.

4.4. Enhanced imaging and interpretation

Enhanced imaging and interpretation in cardiology have undergone a remarkable revolution with the integration of artificial intelligence (AI) technologies [82]. This synergy of advanced imaging modalities and AI-driven tools has brought about transformative changes in the diagnosis, characterisation, and monitoring of cardiovascular diseases [83]. Within this realm, specific diseases have reaped the benefits of these innovations, employing novel AI tools to augment imaging interpretation for more precise diagnoses and enhanced patient care [84].

Companies like HeartFlow have engineered AI algorithms capable of meticulously analysing CT angiography images to assess coronary artery blockages accurately [85]. This technology significantly aids in diagnosing CAD, evaluating the functional significance of lesions, and guiding appropriate treatment decisions [86]. AI-Assisted Cardiac MRI and CT Analysis: Tools developed by Arterys and Siemens Healthineers leverage AI for automated and rapid interpretation of cardiac MRI and CT scans [87]. These AI-driven solutions assist in evaluating cardiac structure, function, and tissue characteristics, enhancing the diagnosis of various cardiac conditions, including myocardial infarction and congenital heart diseases [88].

AI-based software specialises in echocardiography analysis, precisely assessing left ventricular function [89]. This tool detects abnormalities and aids in diagnosing heart failure and valvular diseases, ensuring accurate measurement and characterisation of cardiac function [90]. Research groups have developed AI algorithms for analysing cardiac MRI images to detect and predict the progression of PAH [91]. These AI tools identify subtle changes in cardiac structures, facilitating early diagnosis and effective management [92].

Researchers have devised AI-driven solutions to analyse cardiac MRI images for detecting cardiac tumours [93]. These tools assist in differentiating between benign and malignant tumours, supporting precise treatment planning. AI-Based Electrocardiography (ECG) Analysis algorithms integrated into devices such as the AliveCor KardiaMobile utilise AI for AF detection [94]. They enable continuous ECG monitoring, detecting arrhythmias, and guiding timely interventions. AI-Driven Perfusion Imaging: Various companies, including Canon Medical and HeartFlow, offer AI tools for quantitative analysis of myocardial perfusion using CT and MRI [95]. These tools aid in detecting myocardial ischemia and guiding treatment decisions.

AI-driven enhanced imaging and interpretation tools have significantly bolstered diagnostic accuracy in cardiology, allowing clinicians to discern subtle abnormalities, quantify disease severity, and tailor treatment strategies accordingly. These advancements facilitate early and precise diagnoses, contributing to optimised patient management and improved clinical outcomes across diverse cardiovascular diseases. As AI technologies evolve, the potential to augment imaging interpretation in cardiology further is vast, promising more comprehensive and accurate assessments for better patient care [96].

4.5. Predictive analytics and risk assessment

In cardiology, the integration of predictive analytics and risk assessment powered by artificial intelligence (AI) has ushered in a new era of precision healthcare. Leveraging extensive patient data encompassing clinical records, genetic information, imaging results, and lifestyle factors, these advancements are reshaping how cardiovascular diseases are anticipated, managed, and treated [97]. Various diseases within cardiology benefit from these predictive analytics, employing novel AI tools to foresee disease onset, progression, and potential adverse events [98].

Consider coronary artery disease (CAD), a prevalent cardiovascular condition. Innovations like AI-powered risk prediction models developed by Verily and Duke University harness multifaceted patient data, including genetic markers and imaging, to identify individuals at heightened risk of CAD and subsequent cardiovascular incidents [99]. These predictive models serve as powerful tools for preemptive interventions and targeted preventive measures among high-risk populations, ushering in a new era of proactive healthcare [100].

Heart failure (HF) presents another area where predictive analytics play a crucial role [101]. AI-driven predictive models, such as those developed by Siemens Healthineers, meticulously analyse biomarkers, imaging, and patient history to forecast HF exacerbations [102]. This foresight enables healthcare professionals to tailor personalised care plans, optimise treatment strategies, and mitigate adverse events, thereby enhancing patient outcomes and quality of life for individuals managing HF [103].

Atrial fibrillation (AF), a common arrhythmia, benefits from AI's predictive prowess in genomic analysis [104]. AI algorithms scrutinise genetic data to forecast an individual's response to specific antiarrhythmic medications used in managing AF [105]. Furthermore, cardiometabolic risk assessment and pharmacogenomics advancements underscore AI's role in comprehensive risk evaluation. Technologies from Zebra Medical Vision, Genomic Health, Genuity Science, and others utilise AI algorithms to analyse diverse data sets, from imaging to genetic markers, facilitating early detection, personalised risk mitigation, and tailored medication choices for cardiovascular therapies [105].

4.6. Drug discovery and development

In cardiology, the quest for new treatments and therapies to combat cardiovascular diseases is witnessing a profound transformation, largely thanks to the integration of artificial intelligence (AI) into the drug discovery and development process. This paradigm shift is reshaping how researchers identify potential medications, optimise drug development pipelines, and target specific diseases with a higher degree of precision than ever before. One of the striking trends in contemporary drug discovery involves using AI to identify precise molecular targets implicated in cardiovascular diseases. Companies and research institutions use AI algorithms to sift through massive datasets encompassing molecular and genetic information [106]. This analysis identifies specific pathways and proteins associated with conditions such as atherosclerosis or heart failure, paving the way for targeted therapies designed to intervene at a molecular level [106]. Moreover, the advent of precision medicine in cardiology owes much to AI's ability to analyse vast patient data, including genetic profiles and disease characteristics [107]. AI-driven platforms discern patterns within this data, allowing for the identification of patient subgroups. These insights enable the development of personalised therapies, aligning treatments with individual patient profiles for heightened efficacy and reduced side effects, a promising step towards more tailored and patient-centric cardiovascular care.

Drug repurposing, a strategy gaining momentum in the quest for new cardiovascular treatments, is significantly aided by AI technologies [108]. By sifting through extensive databases and utilising predictive algorithms, AI platforms identify existing drugs approved for other conditions that could be repurposed for cardiovascular diseases [109]. This approach expedites drug development by bypassing some of the lengthy stages of drug discovery, potentially accelerating the availability of new therapies for heart-related conditions.

Table 4 outlines specific cardiovascular diseases and treatment areas, their corresponding focus in AI-driven drug discovery, and examples of AI tools and technologies utilised in each area. These AI-driven initiatives aim to identify novel drug targets, facilitate drug repurposing, and develop tailored treatments, potentially revolutionising cardiovascular care by advancing targeted therapies and personalised medicine.

Table 4
AI-driven drug discovery and development in cardiology.

Cardiovascular Disease and Treatment Area	AI-Driven Drug Discovery Focus	Examples of AI Tools/ Technologies Used
Atherosclerosis and Anti-inflammatory Therapies	Identification of anti-inflammatory targets for atherosclerosis treatment.	- Insilico Medicine's AI algorithms leveraging deep learning and generative models for identifying inflammation pathways and novel targets [110].
Arrhythmias (e.g., Atrial Fibrillation - AF)	Personalized treatments and drug repurposing.	- BenevolentAI's AI-driven drug discovery platforms analyzing patient data for personalized AF treatments [111]. - Atomwise's AI for drug repurposing in AF by screening existing compounds for efficacy [112].
Cardiometabolic Diseases and Targeted Therapies	Identification of compounds targeting cardiometabolic pathways.	- PandaOmics AI-based platform analyzing large datasets to identify compounds targeting cardiometabolic pathways, particularly metabolic syndrome-related pathways [113].
Heart Failure with Reduced Ejection Fraction (HFrEF)	Targeted therapies for HFrEF treatment.	- mirPath AI-driven platform using computational methods and machine learning for identifying small molecules targeting HFrEF-related pathways [114].
Vascular Diseases and Drug Repurposing	Drug repurposing for vascular conditions.	- IBM Watson Health's AI platform analyzing datasets for repurposing drugs in peripheral artery disease and vasculitis [115].

4.7. Clinical decision support systems

Clinical Decision Support Systems (CDSS) in cardiology have witnessed a profound evolution by integrating cutting-edge artificial intelligence (AI) technologies. These systems are designed to assist healthcare professionals in making informed decisions by analysing vast amounts of patient data, medical literature, and clinical guidelines [116]. However, despite their potential, several challenges persist in the implementation and utilisation of CDSS in cardiovascular medicine.

The current trends in CDSS are marked by the utilization of AI algorithms to analyze complex datasets and provide real-time guidance to clinicians [117]. In cardiology, one of the significant challenges CDSS addresses involves risk prediction and stratification for various cardiovascular diseases [116,118]. These systems employ AI tools to assess patient data, including clinical records, imaging results, and genetic profiles, to predict the likelihood of heart attacks, strokes, or arrhythmias [117]. They offer valuable insights into individual patient risk, aiding in personalised treatment planning and early intervention strategies [119].

Another notable application of CDSS is aiding the diagnosis and treatment of coronary artery disease (CAD). Innovative systems, including IBM Watson Health's AI platform, analyse imaging data, clinical records, and guidelines to support clinicians in interpreting complex test results, optimising treatment strategies, and selecting appropriate interventions for CAD patients [120]. These systems aim to enhance accuracy in diagnosis and guide personalised care plans tailored to each patient's unique condition.

Despite the promise of CDSS in cardiology, several challenges impede their widespread adoption and optimal utilisation. Interoperability remains a key hurdle, as integrating these systems with various electronic health record (EHR) platforms and medical devices often presents technical complexities. Additionally, ensuring the accuracy and reliability of AI algorithms used in CDSS poses a significant challenge, as the need for continuous validation and updating of these algorithms is essential to maintain their effectiveness.

Furthermore, integrating CDSS into clinical workflows requires careful consideration to ensure seamless usability without disrupting healthcare provider workflows [117]. Training healthcare professionals to effectively interpret and utilize recommendations from these systems is crucial for their successful implementation [119].

5. Limitations and strengths of this review

While our comprehensive review provides valuable insights into the application of artificial intelligence (AI) in cardiology, several limitations should be acknowledged to ensure the interpretation and generalization of findings.

1. **Data Heterogeneity:** One limitation of our review lies in the heterogeneity of the data sources and methodologies across the included studies. Variability in study designs, patient populations, and AI algorithms may introduce bias and limit the comparability of findings. Future research efforts should aim to standardize methodologies and collaborate across institutions to enhance the robustness and generalizability of results.
2. **Population Diversity:** Another limitation pertains to the lack of diversity in the patient populations included in the reviewed papers. Many papers predominantly focused on populations from high-income countries, limiting the generalizability of findings to diverse populations globally. Future research should strive to include more diverse patient cohorts, encompassing a broader range of demographics, socioeconomic backgrounds, and geographic locations, to ensure equitable representation and applicability of AI-driven interventions in diverse healthcare settings.
3. **Age Group Representation:** Additionally, the age distribution of patients included in the reviewed papers may pose a limitation. While AI-driven interventions show promise across various age groups, the majority of studies primarily focused on adult populations, with limited representation of pediatric and geriatric populations. Future research should address this gap by investigating the efficacy and safety of AI-driven interventions in pediatric and geriatric populations, ensuring inclusivity and tailored approaches across the lifespan.
4. **Data Availability and Quality:** The availability and quality of data represent significant challenges in AI-driven research in cardiology. Limited access to high-quality datasets, especially longitudinal data spanning diverse patient populations, may hinder the development and validation of AI algorithms. Furthermore, issues related to data privacy, security, and interoperability present barriers to data sharing and collaboration across institutions. Addressing these challenges requires concerted efforts to establish standardized protocols for data collection, curation, and sharing while ensuring compliance with regulatory requirements and ethical guidelines.

5.1. *Implication of findings*

The implications of our comprehensive review on the application of artificial intelligence (AI) in cardiology extend across multiple domains, including clinical practice, research, prevention, and policy.

1. **Clinical Practice:** For clinical practice, our review underscores the transformative potential of AI-driven technologies in enhancing diagnostics, personalizing treatment strategies, and improving patient outcomes in cardiology. Clinicians can leverage AI-powered tools to analyze vast and diverse datasets, develop personalized treatment plans tailored to individual patient needs, and predict treatment responses with greater accuracy. By integrating AI-driven solutions into routine clinical workflows, clinicians can streamline decision-making processes, optimize therapeutic strategies, and deliver more precise and effective care to patients.
2. **Research:** In the realm of research, our review highlights the need for continued exploration and innovation in AI-driven cardiology. Future research efforts should focus on addressing key challenges such as data heterogeneity, algorithm bias, and ethical considerations, while also prioritizing interdisciplinary collaboration, data standardization, and personalized medicine approaches. By advancing AI-driven research in cardiology, researchers can unlock new insights into disease mechanisms, develop novel diagnostic and therapeutic interventions, and ultimately improve patient outcomes.
3. **Prevention:** In terms of prevention, AI-driven technologies offer promising opportunities to enhance risk prediction, early detection, and preventive interventions for cardiovascular diseases. By leveraging AI algorithms to analyze diverse patient data, identify high-risk individuals, and implement targeted preventive measures, healthcare providers can mitigate the burden of cardiovascular disease and reduce associated morbidity and mortality. Additionally, AI-enabled remote monitoring and wearable technology empower individuals to actively participate in their health management, facilitating early detection of cardiovascular abnormalities and enabling timely interventions to prevent disease progression.
4. **Policy:** From a policy perspective, our review highlights the importance of establishing regulatory frameworks, ethical guidelines, and governance mechanisms to ensure the responsible deployment of AI technologies in cardiology. Policymakers should prioritize initiatives to address algorithm bias, enhance algorithm interpretability, and safeguard patient privacy and data security in AI-driven healthcare systems. Moreover, efforts to promote health equity, accessibility, and affordability of AI-enabled healthcare services are essential to ensure equitable access to cutting-edge technologies for all patient populations.

5.2. *Future research directions*

Our comprehensive review has shed light on the transformative potential of artificial intelligence (AI) in cardiology. Moving forward, several key areas warrant further exploration and research to advance the field and capitalize on the promises of AI-driven innovation.

1. **Interdisciplinary Collaboration:** Future research efforts should prioritize interdisciplinary collaboration between clinicians, data scientists, engineers, and policymakers to drive innovation and translate AI research into clinical practice effectively. Collaborative initiatives can foster the development of AI-driven solutions tailored to address specific clinical needs, enhance data sharing and interoperability, and ensure the ethical and responsible deployment of AI technologies in cardiology.
2. **Data Standardization and Integration:** Standardizing data collection, curation, and integration processes is crucial for maximizing the utility of AI in cardiology. Future research should focus on developing standardized protocols and frameworks for harmonizing heterogeneous data sources, ensuring data quality, and facilitating interoperability across healthcare systems. Moreover, efforts to integrate AI-driven solutions seamlessly into existing clinical workflows are essential to realize their full potential in enhancing diagnostic accuracy, guiding treatment decisions, and improving patient outcomes.
3. **Personalized Medicine and Predictive Analytics:** Advancements in AI algorithms hold promise for furthering personalized medicine and predictive analytics in cardiology. Future research should explore innovative approaches for integrating diverse patient data, including genetic information, imaging results, and clinical parameters, to develop robust predictive models for risk stratification, treatment response prediction, and disease progression monitoring. By harnessing the power of AI-driven predictive analytics, clinicians can identify high-risk individuals early, tailor treatment plans, and optimize therapeutic strategies to improve patient outcomes and reduce healthcare costs.
4. **Ethical and Regulatory Considerations:** Addressing ethical and regulatory considerations is paramount to the responsible development and deployment of AI technologies in cardiology. Future research should focus on establishing ethical guidelines, regulatory frameworks, and governance mechanisms to ensure patient privacy,

data security, and algorithm transparency. Additionally, efforts to mitigate algorithm biases, enhance algorithm interpretability, and promote algorithmic fairness are essential to building trust and confidence in AI-driven solutions among clinicians, patients, and policymakers.

6. Conclusion

The integration of AI into cardiology has brought about transformative advancements with wide-ranging implications for cardiovascular healthcare. This comprehensive review has highlighted the diverse applications of AI, spanning diagnostic innovations, precision medicine, remote monitoring, enhanced imaging and interpretation, predictive analytics, drug discovery, and clinical decision support systems. These AI-driven technologies have demonstrated the potential to revolutionize traditional approaches to cardiovascular care.

The diagnostic landscape in cardiology has undergone a paradigm shift, with AI-powered algorithms enhancing the accuracy and efficiency of interpreting various diagnostic modalities, from electrocardiograms to cardiac imaging. Precision medicine has emerged as a cornerstone, leveraging AI to tailor treatment plans based on individual patient characteristics, genetic profiles, and disease-specific details. The incorporation of remote monitoring and wearable technology, coupled with AI, has empowered continuous real-time monitoring outside clinical settings, fostering patient engagement and proactive interventions.

Enhanced imaging and interpretation have been significantly bolstered by AI technologies, enabling more precise diagnoses and improved patient care. Predictive analytics and risk assessment, facilitated by AI, are reshaping how cardiovascular diseases are anticipated and managed, allowing for targeted preventive measures. The drug discovery and development process in cardiology has witnessed a profound transformation, with AI playing a pivotal role in identifying molecular targets, enabling drug repurposing, and advancing targeted therapies.

However, alongside these promising advancements, challenges such as algorithm accuracy, interoperability, ethical considerations, and integration into clinical workflows persist. The successful integration of AI into cardiology requires careful consideration of these challenges, necessitating ongoing research, validation, and strategic solutions. As AI-driven technologies continue to evolve, the future of cardiology holds the promise of more personalized, efficient, and effective cardiovascular care. The amalgamation of AI with traditional clinical practices is poised to improve patient outcomes, enhance the precision of diagnostics and treatment strategies, and ultimately shape the future of cardiology practice. Strategic advancements and thoughtful integration of AI have the potential to overcome existing challenges, making cardiovascular healthcare more accessible, proactive, and patient-centric in the years to come.

Ethics approval and consent to participate

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Authors' contributions

DBO conceptualised the study; All authors were involved in the literature review; NA & EK extracted the data from the reviewed studies; All authors wrote the final and first drafts. All authors read and approved the final manuscript.

Consent for publication

Not applicable

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