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REVIEW

Digital Technologies in Cardiology: From Continuous Monitoring to Predictive Medicine

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Abstract: Background: Digital transformation in cardiology is reshaping diagnosis, monitoring, and therapy through connected devices, digital biomarkers, telemedicine, and artificial intelligence. This paper synthesizes recent advances and emphasizes the shift from episodic assessment to continuous surveillance and personalized predictive care. Methods: The article included 81 studies published between 2015 and 2026, identified in PubMed, Google Scholar, and ScienceDirect, encompassing clinical trials, meta-analyses, observational studies, and reviews focused upon continuous cardiovascular monitoring, remote care, and AI-supported analysis. According to the selection criteria, studies with weak methodology or limited clinical relevance were removed. Results: Continuous monitoring enables early detection of physiological changes, improves individualized prevention, reduces hospitalizations, and supports cost efficiency and the expansion of remote services. Artificial intelligence and multimodal analytics facilitate dynamic risk stratification, clinical decision support, and the development of cardiovascular digital twin models for precision medicine. Implementation remains constrained by requirements for robust validation, potential algorithmic bias, data protection and cybersecurity concerns, and regulatory or acceptance barriers. Conclusions: Digital cardiology enables anticipatory, patient-centered healthcare based on continuous monitoring and AI as core clinical tools, promoting integrated patient–hospital–home ecosystems, real-time therapeutic guidance, and sustained cardiovascular prevention. The priorities defined by these directions are subjects for further research and healthcare development worldwide in the next decades.

Keywords: digital health; cardiology; wearable devices; digital biomarkers; biometric sensors; artificial intelligence; telemonitoring; telemedicine platforms; predictive medicine.

INTRODUCTION

Cardiovascular diseases (CVDs) represent the leading cause of morbidity and mortality worldwide, generating a significant burden on healthcare systems. Traditional cardiology is confronted with significant limitations, such as delayed diagnosis, intermittent monitoring, and a predominantly reactive therapeutic approach. In this context, the emergence and integration of digital health technologies mark the transition toward predictive, personalized, and prevention-oriented cardiology. The aim of this article is to analyze the transformation of cardiology through the lens of digital technologies and their impact on the prevention, diagnosis, and management of cardiovascular diseases. Although the evolution of digital technologies in cardiovascular research is relatively recent, their clinical use has demonstrated relevant progress in morbidity and mortality among patients with CVD. From a research perspective, it is essential to understand the emergence of these technologies, their development pace, current themes of interest, and the field's temporal evolution [1].

Technological advances in the diagnosis of cardiovascular diseases also represent a major public health strategy. Integrating these solutions into clinical practice enables

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early detection and the initiation of personalized treatments, with the potential to significantly reduce CVD-associated morbidity and mortality. In addition, the use of telemedicine and telemonitoring contributes to resource optimization and improved access to high-quality medical care, representing an essential step in reducing the global burden of cardiovascular diseases [2]. The development of machine learning (ML) and digital health technologies is redefining the future of cardiovascular prevention. The ability of ML to extract meaningful information from complex medical datasets helps guide clinical decisions; however, this aspect must be balanced against challenges related to privacy, safety, equity, and clinical interpretability [3].

In the future era of digital health, the complex interplay among preventive medicine, primary, secondary, and tertiary prevention will be supported by genomics, artificial intelligence, bioengineering, wearable devices, and telemedicine. Combining these technologies supports a considerable potential of improving medical outcomes and the efficiency of healthcare systems [4]. Artificial intelligence in cardiology must progress beyond simple task automation and should focus on augmenting human clinical expertise, facilitating proactive cardiovascular care based on precision medicine. By leveraging computational advantages while managing its limitations, cardiology is advancing toward an era of transformative innovation beyond the limits of traditional diagnostic and therapeutic paradigms [5]. Systematic literature analyses show that current machine learning methods for diagnosing heart diseases face various challenges, for example, data imbalance, thus limiting their clinical applicability. Nevertheless, these approaches contribute to improving data-driven decision-making processes [6]. Other studies emphasize the critical role of artificial intelligence in rethinking diagnostic and treatment methods to improve patient outcomes [7], as well as emerging trends in supervised prediction algorithms that increase diagnostic accuracy and guide future research directions [8]. In the field of arrhythmia monitoring, long-term continuous ambulatory ECG monitors and external loop recorders have proven more effective than 24-hour Holter monitoring in detecting arrhythmic symptoms, with no significant differences between the two technologies [9]. Moreover, remote patient monitoring interventions can reduce the use of acute care services when designed according to patient characteristics, provider factors, and implementation context [10].

MATERIALS AND METHODS

Study design

The objective of this article is to examine the digital transformation of cardiology, a process that redefines traditional paradigms of diagnosis, monitoring, and treatment through the integration of connected devices, digital biomarkers, telemedicine, and artificial intelligence. The article included studies published between 2015 and 2026 that investigated: the global burden of cardiovascular diseases; the limitations of traditional cardiology (late diagnosis, discontinuous monitoring, reactive treatment); and the emergence and impact of digital health technologies.

Data sources and search strategy

Searches were performed in databases relevant to cardiology and digital technologies applied in cardiology: PubMed, ScienceDirect, and Google Scholar. Search strategies were adapted for each database and included combinations of frequently used field-specific terms connected by Boolean operators (AND, OR): digital health, cardiology, wearable devices, digital biomarkers, artificial intelligence, predictive medicine. Examples of search expressions used: “digital health AND cardiology”, “wearable devices AND cardiovascular disease”, “artificial intelligence AND cardiac diagnosis”, “digital biomarkers AND heart disease”.

Eligibility criteria

Studies were included if they met at least one of the following criteria: clinical, observational, meta-analytical, or review studies relevant to digital health in cardiology; studies evaluating wearable devices, telemedicine, digital biomarkers, or artificial intelligence applications in the prevention, diagnosis, or management of cardiovascular diseases; articles published in English or Romanian between 2015 and 2026. Excluded were: articles without full-text availability; studies not relevant to digital cardiology; duplicate publications or studies with insufficient data.

Study selection

Study selection was conducted in two stages, i.e., screening of titles and abstracts to assess relevance, then an eligibility assessment based on full-text review. Duplicates were removed prior to full-text analysis. A total of 81 studies were ultimately included. The selected studies were analyzed and thematically organized into the main domains of digital health applied in cardiology: wearable devices and continuous monitoring; digital biomarkers; telemedicine and remote management; artificial intelligence and predictive medicine.

RESULTS

1. Wearable devices

We analyze the role of these devices in the screening and remote diagnosis of common cardiovascular diseases, such as arrhythmias, as well as in the management of patients with existing cardiovascular conditions, for example, heart failure. Recent literature provides a comprehensive overview of wearable devices (Table 1). To date, challenges such as device accuracy, clinical validity, the lack of standardized regulatory policies, and concerns regarding patient data privacy continue to limit the widespread adoption of smart wearable technologies in clinical practice. Recommendations for addressing these challenges are presented, along with a simple and practical "ABCD"-type guide tailored to physicians' specific needs, aimed at accelerating the integration of these devices into clinical workflows to optimize patient care [11].

This review synthesizes the characteristics of wearable devices and the associated machine learning techniques. Relevant research studies illustrating the role of these devices in the screening and management of cardiovascular conditions are described, while directions for future research are also identified. Finally, the challenges limiting the widespread use of wearable devices in cardiovascular medicine are highlighted, and short- and long-term solutions are proposed to facilitate their integration into clinical practice [12].

Wearable technology lies at the intersection of precision cardiovascular medicine, providing continuous, non-invasive, evidence-based data on patients' health status. The convergence of AI, the Internet of Medical Things (IoMT), and real-world data integration positions wearable devices as essential tools for risk stratification and remote management. Future directions should prioritize standardized validation frameworks, strengthened cybersecurity, and equitable global access to maximize clinical and population-level impact [13]. Recent data suggest that wearable electrocardiograms perform comparably to conventional monitoring devices and may help reduce healthcare costs. However, challenges related to accessibility, data privacy, and the need to improve accuracy persist. Additional studies are required to critically evaluate existing limitations, given the significant potential of these devices to improve cardiovascular and overall health [14].

Heart failure is a progressive condition associated with increased morbidity and mortality. Early diagnosis and treatment can reduce hospitalizations and readmissions and improve quality of life. Current developments in wearable technology have transformed heart failure management, but their clinical integration requires careful evaluation of technical, clinical, and ethical challenges, including performance, regulation, and data protection [15].

The literature indicates that when integrated with telemonitoring, wearable devices can increase physical activity participation, improving peak oxygen consumption (VO_2peak) and quality of life in patients with coronary artery disease; physical function and quality of life in patients with heart failure; and walking capacity in patients with peripheral artery disease. These devices can detect atrial fibrillation, guide exercise timing, and safely monitor exercise intensity in patients with implantable cardiac devices. Real-time feedback enhances motivation and adherence, amplifying the benefits of cardiovascular rehabilitation programs [16].

Devices such as Apple Watch Series 9, Fitbit Charge 6, Garmin vívosmart 5, and Oura Ring Gen3 have proven suitable for monitoring cardiovascular function in community-dwelling adults. The systematic selection approach can also be extended to other physiological and behavioral variables [17].

Algorithms based on smartwatches show a strong correlation with atrial fibrillation burden determined by implantable cardiac monitoring and high clinical sensitivity for detecting recurrences, outperforming conventional non-invasive strategies. These findings support their use as a scalable alternative for rhythm monitoring after ablation [18].

Available data indicate excellent diagnostic accuracy, suggesting that these devices may represent an appropriate and accessible option for patients [19]. They demonstrate high diagnostic performance for atrial fibrillation and ST-segment abnormalities, especially in supervised settings. However, inconclusive recordings and algorithmic limitations remain important barriers, requiring real-world validation and algorithm optimization [20].

Compared with traditional methods, smartwatches enable more efficient detection of recurrences, characterization of arrhythmic burden, symptom–rhythm correlation, and increased patient engagement. Nevertheless, limitations such as motion artifacts, false-positive alerts, dependence on adherence, and issues related to regulation, interoperability, and privacy persist. Integrating these technologies into evidence-guided care pathways could allow more proactive and personalized management of atrial fibrillation [21].

The integration of wearable technology into healthcare systems can be helpful in facilitating early diagnosis, patient engagement, and continuous monitoring of cardiac health. Despite ethical considerations and inequalities in access, the potential benefits outweigh the challenges. Increased awareness, interdisciplinary collaboration, and further research are needed to optimize accuracy and support the widespread adoption of these technologies [22].

Table 1: Scientific articles presenting studies on digital health in cardiology – Wearable devices

Focus / Application	Year	Author	Conclusions
Smart wearable devices in cardiovascular care (screening, remote diagnosis, management)	2021	Bayoumy K. [11]	Wearable devices can support remote detection and diagnosis of cardiovascular diseases, including arrhythmias, and monitoring of patients with existing cardiovascular disease, such as heart failure. Widespread adoption is limited by accuracy, clinical validity, uneven regulation, and privacy risks; structured integration into clinical workflows is needed.
Wearable devices in cardiovascular medicine (features, data analysis, research directions)	2023	Hughes A. [12]	Wearables, together with advanced data analytics and machine learning, have potential in cardiovascular screening and management. Barriers to large-scale use remain, including validation, interoperability, and digital equity, requiring both short- and long-term solutions.
Wearable technology for cardiovascular health monitoring and disease management (precision medicine)	2025	Nazir A. [13]	Wearable technology can provide continuous, noninvasive, clinically useful data, especially when combined with artificial intelligence, the medical Internet of Things, and real-world data. Standardized validation frameworks, improved cybersecurity, and equitable global access are required.
Wearable technology in cardiology: advances, applications, and perspectives	2025	Jena N. [14]	Electrocardiograms obtained with wearable devices may achieve performance comparable to conventional monitoring and reduce costs. Challenges persist in accessibility, privacy, and the need for improved accuracy; further critical evaluations are required to confirm benefits and define limitations.
Wearable devices for monitoring and management of heart failure	2024	Odeh V.A. [15]	Wearable technology may improve early diagnosis and management of heart failure, with potential to reduce hospitalizations and improve quality of life. Clinical integration requires addressing technical performance, regulatory requirements, and data privacy.
Wearable devices for exercise prescription and physical activity monitoring in patients with cardiovascular disease	2025	Terada T. [16]	Wearables, especially when combined with telemonitoring, can increase participation in physical activity and improve functional capacity and quality of life across multiple cardiovascular conditions. They may also help differentiate atrial fibrillation from sinus rhythm and safely monitor exercise intensity; effectiveness depends on consistent use and integration into care.
Practical guide for selecting wearable devices measuring cardiovascular functions in the general population	2025	Lu J.K. [17]	A systematic device-selection process, illustrated with commercial models, can identify suitable options for measuring cardiovascular function in community-dwelling adults. The method can be extended to other physiological and lifestyle variables.
Detection and estimation of atrial fibrillation burden after ablation using smartwatches compared with continuous implantable monitoring	2025	Aguilar M. [18]	Smartwatch algorithms may correlate well with atrial fibrillation burden measured by continuous implantable monitoring and detect recurrences with good clinical sensitivity. Findings support their use as a scalable alternative for post-ablation rhythm monitoring.
Accuracy of smartwatches in detecting atrial fibrillation (systematic review and diagnostic meta-analysis)	2025	Barrera N. [19]	Smartwatches may show very good diagnostic accuracy for atrial fibrillation detection and represent a suitable option for screening and monitoring, provided correct use and clinical confirmation when necessary.
Diagnostic accuracy of wearable electrocardiography for atrial fibrillation and ST-segment changes (systematic review)	2025	Sîngeap M.S. [20]	Wearable ECG devices can effectively detect atrial fibrillation and ST-segment abnormalities, especially in supervised settings. Inconclusive recordings and algorithm limitations remain barriers; real-world validation and algorithm improvements are needed.
Monitoring atrial fibrillation through wearable digital technologies: the role of smartwatches	2025	Stachteas P. [21]	Smartwatch monitoring may improve recurrence detection, AF burden estimation, symptom–rhythm correlation, and patient engagement. Limitations include motion artifacts, false-positive alerts, short recordings, reliance on adherence and digital literacy, access inequities, and regulatory, interoperability, and privacy issues; promising as a complement to established methods.
Applications of smartwatches in atrial fibrillation detection: present and future directions	2024	Vyas R. [22]	Integration of wearable technology may enable earlier diagnosis, better engagement, and improved cardiac monitoring. Institutional collaboration, accuracy optimization, and implementation support are required, with attention to ethical considerations and disparities.

2. Digital biomarkers

Heart rate variability (HRV) indicates autonomic regulation and has become a digital biomarker with improtant applications in both clinical care and operational performance. Recent literature provides a comprehensive overview of digital biomarkers (Table 2). Considering HRV as a dual-use tool enables the connection between the medical field and operational human performance: the same cardiac data that can anticipate clinical events in patients may also signal the risk of exhaustion or overload in high-stress professional contexts. However, optimal use of this biomarker requires continuous data collection, validated artificial intelligence algorithms, privacy protection, and clear usage guidelines. Under these conditions, HRV becomes not only a monitoring tool but also a practical and ethical support for decision-making in clinical and operational environments [23].

The coefficient of variation of heart rate variability (HRV-CV) serves as an indicator of daily cardiac autonomic fluctuations and has potential as a scalable digital biomarker for behavioral monitoring and health risk stratification. Measuring HRV-CV during sleep provides a robust estimate of daily HRV variability; an analysis of nearly two million recordings from more than 21,000 individuals demonstrated that five nights of monitoring are sufficient for reliable seven-day estimates. Higher HRV-CV values are associated with greater alcohol consumption, lower physical activity levels, reduced sleep duration and regularity, older age, and increased body mass index (BMI). These findings provide the first large-scale characterization of HRV-CV and support its utility for behavioral monitoring and risk stratification [24].

In recent years, clinical evidence regarding digital biomarkers has been systematically evaluated across a variety of populations, interventions, devices, and sensor technologies, with a predominance of physical activity measurements and cardiac monitoring. The classification of behavioral and physiological data using the World Health Organization's ICF framework has proven applicable for organizing the wide range of identified digital biomarkers. Determining the true clinical value of these biomarkers requires systematic assessment of the quality and consistency of evidence regarding their impact on health outcomes [25].

Telemetry units are useful for providing continuous monitoring of vital signs and electrocardiographic data, parameters that function as digital signatures of physiological status and may facilitate the detection of anomalies preceding cardiac arrest. The available data suggest that dynamic changes in vital signs may contribute to the prediction of in-hospital cardiac arrest. However, there is still no consensus regarding the optimal methods for analyzing these digital biomarkers, and large prospective studies are needed to validate their predictive value in clinical practice [26].

Table 2: Scientific articles presenting studies on digital health in cardiology – Digital biomarkers

Focus / Application	Year	Author	Conclusions
Heart rate variability as a dual-use digital biomarker (clinical and operational)	2026	Burlacu A. [23]	Heart rate variability reflects autonomic regulation and can function as a digital biomarker in both clinical care and the assessment of performance and resilience. Responsible use requires consistent data collection, trustworthy AI-based analysis, protection of privacy, and clear rules for ethical implementation.
Coefficient of variation of heart rate variability during sleep as a behavior-associated digital biomarker	2026	Grosicki G.J. [24]	The coefficient of variation of heart rate variability during sleep may be a scalable digital biomarker for monitoring behaviors and risk stratification. A small number of nights can provide reliable estimates, and higher values are associated with increased alcohol consumption, lower physical activity, shorter and less consistent sleep, older age, and higher body mass index.
Studies based on digital biomarkers: synthesis of systematic analyses (scoping review)	2022	Motahari-Nezhad H. [25]	Evidence on digital biomarkers is extensive and includes diverse populations, interventions, and sensors, with predominance of physical activity monitoring and cardiac parameters. Standardized data classification helps structure the field, but clinical value requires systematic evaluation of evidence quality and impact on health outcomes.
Prediction of cardiorespiratory arrest using digital biomarkers (systematic review)	2023	De Sario Velásquez G.D. [26]	Continuous monitoring of vital signs and electrocardiography can identify changes preceding cardiac arrest, suggesting predictive utility. There is no consensus on optimal analytical methods; rigorous large-scale prospective studies are needed to confirm predictive value.

3. Biometric sensors

Recent literature provides a comprehensive overview of biometric sensors (Table 3). CVDs are still among the leading causes of mortality worldwide, tehrefore long-term and real-time monitoring of cardiovascular parameters is essential for the early identification of abnormalities and the initiation of interventions at the optimal moment. In this context, research interest has shifted toward developing flexible, wearable, or implantable sensors capable of continuously recording relevant physiological indicators. Among the available categories, mechanical sensors can directly reflect pressure fluctuations in the heart and blood vessels, offering high sensitivity and versatility. Four major classes of mechanical sensors—capacitive, piezoresistive, piezoelectric, and triboelectric—are described as recent developments for cardiovascular monitoring. Relevant biomechanical phenomena (e.g., arterial and endocardial pressure, pulse wave, and heart rhythm) and associated monitoring methods are also presented. Finally, the usefulness of continuous monitoring in the management of vascular diseases and the barriers to its translation into clinical practice are discussed [27].

Continuous monitoring of cardiovascular parameters can facilitate early detection of clinical deterioration and timely intervention. The development of flexible wearable/implantable sensors has accelerated, and mechanical sensors have emerged due to their ability to capture pressure variations within the cardiovascular system, combining high sensitivity with adequate flexibility for prolonged use. The paper synthesizes recent advances in sensors based on capacitive, piezoresistive, piezoelectric, and triboelectric principles, as well as the physical-mechanical mechanisms that can be monitored (pulse wave, blood pressure, heart rhythm, endocardial pressure). Challenges related to clinical implementation and the importance of real-time monitoring in the treatment of cardiovascular diseases are also highlighted [28].

Continuous blood pressure (BP) monitoring is highly relevant for real-time surveillance and early prevention of cardiovascular diseases. Wearable devices intended for BP monitoring have advanced significantly through adaptations to long-term wearability and improved comfort, but their development remains constrained by challenges such as motion artifacts and insufficient dynamic response. Methods based on pulse transit time, which combine photoplethysmographic (PPG) signals with electrocardiography (ECG), have attracted attention due to their potential for high accuracy and superior dynamic response [29].

Table 3: Scientific articles presenting studies on digital health in cardiology – Biometric sensors

Focus/application	Year	Author	Conclusions
Biomechanical detection systems for monitoring cardiac activity	2022	Owida H.A. [27]	Flexible wearable or implantable sensors can enable continuous, real-time cardiovascular monitoring, such as pressure, pulse wave, and heart rate, with potential for early intervention. There are advantages in accuracy and versatility, but translation into clinical practice remains difficult due to technical and implementation challenges.
Mechanical sensors for cardiovascular monitoring: from battery-powered to self-powered	2022	Tang C. [28]	Flexible mechanical sensors can directly reflect pressure fluctuations in the cardiovascular system and support long-term monitoring. Self-powered solutions are promising; however, challenges remain for clinical use and integration into real-time physiological monitoring.
Continuous wearable blood pressure monitoring based on pulse transit time and pulse arrival time (review)	2023	Zhou Z.B. [29]	Continuous blood pressure monitoring with wearable devices is advancing, and methods combining photoplethysmographic signals with electrocardiography can provide good dynamic response and accuracy. Nevertheless, motion noise and response limitations remain major issues; improvements are needed for reliable daily use.

4. Telemonitoring and telemedicine platforms

Telemedicine can facilitate the timely delivery of preventive interventions, potentially reducing cardiovascular morbidity and mortality. Recent literature provides a comprehensive overview of telemonitoring and telemedicine platforms (Table 4). The virtual implementation of prevention may help reduce pressure on hospitals by decreasing the incidence of acute cardiovascular events and limiting unnecessary presentations to medical facilities. Telemedicine platforms enable periodic check-ups, monitoring, and early interventions, supporting the prevention of acute events and slowing the progression of cardiovascular diseases [30]. The use of telehealth is increasing at multiple levels of healthcare systems; however, integration into primary care remains uneven. The paper synthesizes the characteristics, approaches, and dimensions of telehealth in this context, highlighting that it can support a wide range of activities through broadly accessible communication channels. Due to the opportunistic use of existing devices and platforms, telehealth can be scaled nationally and internationally. Nevertheless, technical, organizational, and human barriers persist; in particular, digital equity (access to technology and digital health literacy) is critical for extending services to underserved populations [31].

Telemedicine, defined as the provision of clinical services at a distance through digital technologies, is an important direction of research in contemporary cardiology. Follow-up consultations conducted via health applications can improve efficiency and adherence, reducing missed appointments and facilitating monitoring. Implementation requires adequate infrastructure (high-quality audio-video, document management, and payment solutions), as well as patient engagement in transmitting relevant information. However, telemedicine complements rather than replaces the physical consultation. Its usefulness has been highlighted especially in contexts with limited access to services, including during public health crises [32]. The use of telehealth for hypertension and cardiovascular diseases has increased, particularly during the COVID-19 pandemic [33]. The analyzed interventions targeted patients with hypertension, heart failure, and stroke and frequently employed team-based care models (physicians, nurses, pharmacists, and other professionals). Results suggest that telemedicine is generally comparable to traditional face-to-face care for blood pressure control and cardiovascular disease management, functioning as an extension of care for certain patient groups. It may also support communication, engagement, and monitoring outside the clinical setting [34].

Heart failure remains a major public health issue, and remote monitoring and telemedicine can support personalized interventions, including through the integration of artificial intelligence and machine learning. The need for continuous innovation, interdisciplinary collaboration, and strategic investment is emphasized to harness the transformative potential of these solutions toward patient-centered care and efficient resource use [35].

Evidence from randomized trials and meta-analyses indicates that telemedicine can improve the implementation of guideline-directed therapy, reduce hospitalizations, increase patient engagement, and, in some contexts, reduce mortality. Remote monitoring of vital signs, symptoms, and treatment adherence can enable early detection of clinical deterioration and intervention before decompensation, but barriers must also be considered, e.g., technological limitations, reimbursement challenges, gaps in digital literacy, and integration into clinical workflows. Future directions in this field must be focused on standardized guidelines, patient-centered design, and hybrid models (virtual plus face-to-face) [36]. Internet-based remote monitoring systems can facilitate rapid responses to emergencies, reduce resource utilization, and improve clinical outcomes in the management of chronic diseases. Strategies that combine automated data collection, patient self-reporting, and personalized communication are recommended to overcome obstacles to sustained behavioral change and quality-of-life improvement [37].

Analyses indicate improvements in outcomes, access, and patient satisfaction—especially in chronic disease management—through reduced geographic barriers and increased engagement, and, similarly, comprehensive evaluations show a favorable impact on clinical outcomes, cost savings, and higher satisfaction levels, suggesting transformative potential for healthcare delivery [38,39]. Telemedicine may be able to improve the accessibility of specialized cardiology care, including in rural and underserved areas, facilitating cardiac rehabilitation and reducing health disparities [40]. As technology advances, the role of telemedicine in cardiology is expected to grow, influencing efficiency, costs, and patient management; at the same time, implementation and regulatory challenges remain relevant [40]. Digital health tools can improve access to care and outcomes in rural populations through teleconsultations, remote monitoring, mobile applications, and wearable devices. Major barriers remain limited connectivity and low familiarity with digital technologies—issues that must be addressed to ensure equitable access and sustainable implementation [41].

Table 4: Scientific articles presenting studies on digital health in cardiology – Telemonitoring and telemedicine platforms

Focus / Application	Year	Author	Conclusions
Telemedicine in personalized prevention of cardiovascular diseases (systematic review)	2021	Battineni G. [30]	Telemedicine can facilitate cardiovascular prevention through timely interventions, with the potential to reduce morbidity and mortality and decrease pressure on hospitals. It can support regular check-ups and prevent disease progression, reducing unnecessary visits.
Telehealth in primary health care (scoping review)	2022	Beheshti L. [31]	Telehealth can be implemented in primary care using existing communication channels and can provide scalable services. Technical, organizational, and human barriers exist, and digital equity—through access and online health literacy—is essential for expansion to underserved populations.
Telemedicine: capabilities, characteristics, barriers, and applications	2021	Haleem A. [32]	Telemedicine can improve efficiency and continuity of care through audio-video consultations and management systems. It does not replace the physical consultation and remains a complementary tool, especially useful when access to medical services is limited, such as during epidemic contexts.
Telehealth for cardiovascular disease and hypertension (systematic review and meta-analysis, 2011–2021)	2023	Jackson T.N. [34]	Telehealth interventions for hypertension, heart failure, and stroke are often team-based and can be comparable to face-to-face care for blood pressure control. They may improve communication, patient engagement, and monitoring outside the clinic.
Remote monitoring and telemedicine in heart failure management	2024	Liu J.C. [35]	Heart failure management can benefit from remote monitoring and telemedicine, including personalized interventions supported by artificial intelligence and machine learning. Interdisciplinary

			collaboration and investment are required for integration into patient-centered care.
Telemedicine in heart failure treatment: evidence, limitations, and directions	2025	Choi D.J. [36]	Telemedicine interventions can improve guideline-directed therapy use, reduce hospitalizations, and increase patient engagement, with a possible mortality-reducing effect. Barriers include technological limitations, reimbursement, digital literacy, and workflow integration; hybrid models and standardized guidelines are recommended.
Internet-based remote monitoring for chronic diseases in Asia (systematic review)	2025	Emaliyawati E. [37]	Internet-based remote monitoring can reduce healthcare utilization and improve clinical outcomes in chronic diseases. For sustainable effects, combining automated data collection with patient reporting and personalized communication is important, addressing behavioral-change challenges.
Telemedicine: outcomes and access to care (systematic review)	2024	Ezeamii V.C. [38]	Telemedicine can increase access and patient satisfaction and improve outcomes in chronic diseases. Implementation should pursue equity and integration into patient-centered care.
Impact of telemedicine and remote patient monitoring on care delivery (comprehensive evaluation)	2024	Vudathaneni V.K.P. [39]	Improvements in patient outcomes, cost savings, and increased satisfaction are reported. Telemedicine and remote monitoring can transform care delivery if coherently integrated into health systems.
Telemedicine in cardiology: access to care and patient outcomes	2024	Tolu-Akinnawo O. [40]	Telemedicine can improve access to specialized cardiology care, including in rural settings, and can support cardiac rehabilitation, reducing disparities. Implementation and standardization challenges must be addressed.
Digital solutions for reducing care gaps in rural areas (scoping review)	2024	Maita K.C. [41]	Digital tools such as teleconsultations, remote monitoring, mobile applications, and wearable devices can improve access and outcomes in rural areas. Limited internet connectivity and low technological familiarity are major barriers that must be addressed to ensure equity.

5. Artificial Intelligence

Artificial intelligence and ML are increasingly influencing cardiovascular medicine by providing tools for predictive modeling, diagnosis, risk stratification, and decision support (Table 5). Relevant concepts in cardiology are discussed (e.g., feature selection and common methodological errors), along with supervised learning algorithms and their current applications, as well as the role of deep learning and unsupervised methods in analyzing complex data. Overall, AI is capable of contributing to precision cardiology and improved clinical outcomes, although integration into routine practice remains limited [42]. Despite advances in diagnosis and treatment, cardiovascular diseases remain a leading cause of morbidity and mortality. AI has the potential to transform cardiology practice, particularly in medical imaging and the interpretation of complex datasets, by supporting clinical decision-making and extracting clinically relevant information. Integration with digital communication technologies may enable home-based care models for elderly and chronically ill patients, reducing hospitalizations and improving quality of life. Reviews highlight the potential of AI in both imaging and clinical practice, as well as the need to address limitations and ethical considerations [43].

AI can support the prediction of cardiovascular outcomes, the noninvasive diagnosis of coronary artery disease, the detection of arrhythmias via wearable devices, and the optimization of heart failure management. The development of IoT and precision medicine is accelerating their integration. However, ethical and real-world implementation concerns remain, requiring robust governance frameworks and clinical validation [44]. AI is integrated into clinical decision support systems (CDSS) using either rule-based approaches or data-derived ML models. Techniques such as artificial neural networks and support vector machines have evolved, and increased computational power has enabled the development of deep neural networks (DNNs). Despite their promise, the current impact on clinical practice is still moderate; however, the rapid expansion of the literature suggests an increasingly important role in the field [45]. Methodological reviews describe AI workflows, common algorithms for regression and classification, and performance metrics. The role of explainable artificial intelligence (XAI) in enhancing model transparency and trust is emphasized. Applications in cardiology involving supervised learning, unsupervised learning, reinforcement learning, and natural language processing are reviewed, highlighting the need for legal, ethical, and methodological requirements for clinical implementation [46].

AI and ML can improve diagnostic accuracy, risk prediction, workflow efficiency, and resource utilization. Applications in imaging, major categories of cardiovascular diseases, clinical research, and outcome prediction are summarized, along with discussions of the algorithms and methodologies used. Nevertheless, limitations persist regarding generalizability, data quality, bias, interpretability, and integration into clinical processes [47]. In cardiovascular medicine, the main objectives of AI include optimizing care, increasing efficiency, and improving clinical outcomes in the context of expanding data sources and therapeutic advances. Editorials highlight research priorities and the need for concrete steps toward responsible clinical implementation [48].

Narrative syntheses show that AI models have been widely applied to ECG and imaging data (echocardiography, coronary angiography, cardiac CT, and cardiac MRI), targeting diagnosis and risk stratification for multiple pathologies (e.g., coronary artery disease, cardiomyopathies, arrhythmias, and valvular diseases). Overall, the integration of AI promises significant advances in diagnosis and treatment, provided that clinical validation and ethical implementation are ensured [49].

Table 5: Scientific articles presenting studies on digital health in cardiology – Artificial intelligence

Focus / Application	Year	Author	Conclusions
Artificial intelligence in cardiology: framework for clinicians and applications	2018	Johnson K.W. [42]	Artificial intelligence and machine learning can influence prediction, diagnosis, and decision support in cardiology. Proper application requires solid predictive modeling principles, avoidance of methodological errors, and careful integration of advanced methods for precision cardiology.
Artificial intelligence and cardiovascular diseases: applications and role in practice	2020	Romiti S. [43]	Artificial intelligence can improve data interpretation and clinical decision-making, especially in imaging, by leveraging large data volumes. Digital technologies may support home care for elderly and chronically ill patients, reducing hospitalizations and improving quality of life.
Artificial intelligence in cardiology: current utility and perspectives	2022	Karatzia L. [44]	AI models can support outcome prediction, noninvasive diagnosis, arrhythmia detection via wearable devices, and heart failure management. Ethical dilemmas and real-world implementation challenges remain.
Artificial intelligence in cardiology: current status (narrative review)	2022	Koulaouzidis G. [45]	AI is important in clinical decision support systems and is rapidly advancing due to computational power and deep learning. Although routine clinical impact is still limited, applications are expanding and suggest increasing integration into cardiology.
Artificial intelligence technologies in cardiology: algorithms, evaluation, and explainable AI	2023	Ledziński Ł. [46]	Safe adoption requires understanding workflow, selecting appropriate algorithms, rigorous performance evaluation, and the use of explainable methods. Clear legal, ethical, and methodological requirements are needed for medical implementation.
Artificial intelligence in cardiovascular diseases: clinical applications, models, and limitations	2025	Chowdhury M.A. [47]	AI can increase diagnostic accuracy, disease prediction, workflow efficiency, and resource utilization in cardiovascular diseases. Real impact requires validation, clinical integration, and management of limitations to reduce errors and improve monitoring and decision-making.
Role of artificial intelligence in cardiology (editorial)	2023	Vidal-Pérez R. [48]	Major objectives include optimizing care, increasing efficiency, and improving clinical outcomes. The field benefits from large data volumes and technological advances, but implementation must be responsible and guided by clear research priorities.
Future horizons for artificial intelligence in cardiology (narrative review)	2024	Patrascanu O.S. [49]	AI models applied to electrocardiography, echocardiography, coronary angiography, computed tomography, and cardiac magnetic resonance can improve diagnosis and risk assessment for many cardiovascular diseases. Integration promises benefits, provided rigorous validation and safe implementation.

DISCUSSION

1. Continuous digital cardiovascular monitoring

The transition from episodic monitoring toward continuous, discreet surveillance is integrated into everyday life.

The digitalization of cardiovascular monitoring has accelerated a shift in the clinical paradigm—from point-in-time ("snapshot") assessments to longitudinal monitoring capable of capturing rare, intermittent, or asymptomatic events. In this context, wearable and implantable devices, along with contactless solutions, are shaping an "invisible" clinical surveillance infrastructure with the potential for early detection, dynamic risk stratification, and timely intervention.

Wearable devices and portable sensors

Electrocardiography (ECG) remains the reference tool for evaluating cardiac electrical activity, and the 12-lead ECG is the diagnostic standard for multiple non-arrhythmic pathologies. However, the technical complexity of acquisition and reliance on trained personnel limit its use outside medical settings. Portable ECG devices and remote monitoring solutions have sought to reduce this gap through simplified acquisition (typically single-lead), facilitating self-monitoring and extending surveillance into ambulatory environments.

An analysis of studies conducted on commercially available devices validated in adult populations and approved by the FDA indicates that reduced-lead ECG devices have significant potential for long-term monitoring, especially when combined with real-time alert mechanisms. Their clinical utility is particularly relevant for identifying abnormal rhythms, with evidence suggesting that certain remote devices may surpass conventional ECG in diagnosing specific arrhythmias, such as atrial fibrillation. Despite these advantages, limitations persist regarding signal quality, device reliability, and the relatively small number of robust clinical studies evaluating their impact on therapeutic decision-making and clinical outcomes [50].

In parallel, smartwatches have evolved into multifunctional platforms with medical applications that can be grouped into three domains: monitoring, nudging, and prediction. Monitoring refers to the integration of data into medical management; nudging involves individual use aimed at behavior change; and prediction leverages aggregated data to train machine-learning algorithms to anticipate health outcomes. The literature highlights the potential of these devices within value-based medicine, while also emphasizing the need for more nuanced discussions regarding validation, clinical use, and the ethical implications of predictions generated from population-level data [51].

Implantable devices and ECG patches

Wireless transmission and ECG digitalization have facilitated the implementation of continuous monitoring strategies, with a major impact on the diagnosis and management of dysrhythmias. Implantable loop recorders (ILRs) represent a technologically mature option for long-term monitoring, with increasingly well-defined indications (e.g., unexplained syncope, suspected paroxysmal arrhythmias, post-event monitoring). Recent analyses highlight device progress and development directions, including optimization of detection algorithms and integration into clinical telemonitoring workflows [52].

In populations at risk of developing atrial fibrillation after specific interventions, ILR may overcome the limitations of prolonged external monitoring, which is often impractical. For example, in patients with atrial flutter undergoing cavotricuspid isthmus ablation, long-term ECG monitoring may reveal the onset of new atrial fibrillation, frequently within the first months after the procedure; ILR thus becomes a realistic solution for continuous surveillance, with implications for thromboembolic event prevention and therapy adjustment [53].

In cryptogenic stroke, underdiagnosed atrial fibrillation remains a major clinical issue. Evidence indicates that extended monitoring can increase detection rates, yet many studies present significant “gaps” in monitoring intervals, especially immediately after the index event. In addition to ILR, noninvasive strategies such as external loop recorders (ELR) and mobile cardiac outpatient telemetry (MCOT) are used; however, the relative role of wearable devices and “smart” monitoring in prevention remains insufficiently clarified. A synthesis of the evidence underscores the need for more precise recommendations regarding patient selection for each technology and for studies that reduce existing methodological gaps [54].

Contactless monitoring

Contactless monitoring, particularly during sleep, addresses a clinical and operational need: reducing the intrusiveness of polysomnography (PSG) and extending evaluation into non-hospital environments. A systematic review of contactless technologies describes a variety of sensors and systems (e.g., radar, temperature sensors, motion sensors, video cameras) capable of estimating cardiorespiratory parameters with minimal patient impact. Additionally, advantages and limitations related to accuracy, robustness to artifacts, and implementation conditions in clinical or home environments are identified [55].

Radars for vital sign detection offer distinct benefits: elimination of electrodes, freedom of movement, reduction of skin irritation, and facilitated patient access (particularly relevant in children and older adults). However, broad clinical acceptance depends on overcoming technical and validation barriers, especially regarding signal reliability under real-world conditions [56]. In the same direction, the use of IR-UWB radar for measuring multiscale cardiac motion proposes a contactless alternative for rapid and potentially accurate assessment, with promising applications in online monitoring and home care [57].

Video photoplethysmography (vPPG/rPPG/iPPG) represents another emerging direction. However, blood pressure estimation via vPPG is limited by low signal-to-noise ratio and variability in the correlation between pulse transit time and blood pressure, with performance dependent on method and analyzed region of interest (e.g., facial regions vs. hand) [58]. By comparison, evaluation of pulse frequency characteristics and variability through iPPG indicates that certain methods (such as POS and CHROM) may be more robust to motion and illumination artifacts, supporting the clinical potential of these systems for assessing autonomic nervous system dynamics, including through derived indicators (e.g., Poincaré maps) [59].

Continuous cardiovascular monitoring is emerging as a next-generation clinical infrastructure, but its large-scale implementation requires standardization, real-world validation, interoperability, and responsible integration into clinical workflows.

2. Artificial Intelligence in Cardiology

Cardiology is becoming anticipatory, personalized, and decision-oriented, not merely diagnostic.

AI is transforming cardiology through its ability to integrate large volumes of data (ECG, imaging, clinical data, sensors) and generate inferences that support clinical decisions. Beyond algorithmic performance, the critical challenges remain interpretability, generalization across diverse populations, bias control, and evaluation of real clinical impact.

ECG analysis through Deep Learning

Advances from 2017–2023 show a substantial increase in performance in arrhythmia detection and classification, with deep learning models frequently outperforming classical ML approaches. Various architectures are used (CNNs, RNNs, transformers, hybrid models), and the literature highlights both improved accuracy and the need for methodological guidelines regarding comparability, dataset selection, and external validation [60–62].

Recent directions include computationally efficient models adapted to resource-limited devices such as wearable monitors. For example, a lightweight 1D architecture based on ConvNeXtV2 demonstrated high performance in detecting atrial fibrillation and atrial flutter from single-lead ECG, while maintaining low computational cost and offering interpretability elements through Grad-CAM visualizations (attention to P-wave morphology and RR irregularities) [63].

AI in cardiac imaging

AI is increasingly applied in cardiovascular CT and MRI, with reported benefits for workflow (acquisition/post-processing time), image quality, and diagnostic accuracy. Applications include automated calcium scoring, stenosis quantification, plaque analysis, segmentation, and volumetric quantification, as well as myocardial tissue characterization [64,65].

In low- and middle-income countries, AI may facilitate task-shifting to less experienced operators; however, implementation depends on dataset diversity, infrastructure, governance, and ethical frameworks. Available reviews emphasize the need for multicenter data sharing, training, and interoperability standards [66]. A complementary direction is explainable AI (XAI), necessary to increase trust and clinical integration; however, XAI evaluation remains predominantly qualitative and insufficiently standardized [67].

Fusion modeling (clinical data + imaging) indicates prognostic improvements compared with traditional scores, but requires automated feature extraction from electronic health records and images—using CNNs and NLP—to become feasible in practice [68].

Clinical decision support systems

AI-based clinical decision support systems (CDSS) are considered a major direction for improving decision quality and patient outcomes. The literature highlights both applications (assisted diagnosis, personalized therapeutic recommendations, risk prediction, clinical documentation) and barriers: interpretability, bias, workflow integration, accountability, and medico-legal aspects [69].

Proof-of-concept studies show the possibility of predicting ischemic events over short time windows with accuracies >80% and potential for proactive intervention; however, translation into clinical implementation requires external validation, assessment of clinical benefit, and error analysis [70]. An important conceptual shift is the transition from “prediction” to patient-centered decision intelligence through multimodal integration (clinical notes, wearables, social determinants, environmental factors) and the provision of actionable, explainable, and context-sensitive recommendations [71].

3. From digital medicine to predictive medicine

Cardiology is evolving toward an anticipatory and personalized model based on dynamic risk and multimodal data.

Personalized risk models

Risk models increasingly guide clinical decisions, including in heart failure and cardiomyopathies. For example, in heart failure with preserved ejection fraction, a model using widely available variables can identify patients at high risk of sudden cardiac death, supporting stratification and differentiated monitoring [72].

In primary cardiomyopathies, risk assessment requires a multiparametric, stepwise approach that integrates clinical evaluation, ECG monitoring, multimodal imaging, genetics, and electroanatomical mapping, with implications for ablation and ICD indication [73,74]. In addition, the limitations of static models and surrogate criteria (e.g., appropriate ICD therapy), which may overestimate “true” risk and lead to unnecessary interventions, are emphasized; thus, dynamic models and disease-specific endpoints are needed [74,75]. The integration of machine learning in predicting mode of death and risk stratification, including in advanced imaging contexts, supports the shift toward individualized assessment; however, robustness, transparency, and clinical validation remain essential conditions [74,76].

Digital biomarkers and precision cardiology

Digital biomarkers (derived from sensors, wearables, and implantable devices) extend clinical observation beyond the hospital and may support therapeutic decisions. A synthesis of meta-analyses indicates evidence of variable quality: some interventions based on digital biomarkers are associated with meaningful improvements (including arrhythmia detection and reduced stroke incidence in certain contexts), yet reporting quality is often low. Rigorous use of AMSTAR-2 and GRADE tools is recommended to strengthen the evidence base [77].

Scoping reviews show rapid expansion of the field but also a lack of uniform operational definitions and standards for integrating digital biomarkers into practice, highlighting the need to map evidence across clinical domains and identify gaps [25]. Heart rate variability (HRV) is an example of a digital biomarker with clinical and operational utility, but effective implementation depends on standardized acquisition, context-dependent interpretation, and environment-specific validation [23].

The cardiovascular digital twin

The concept of the cardiac digital twin promises a personalized in silico representation, dynamically updated with clinical and monitoring data, capable of simulating disease progression and treatment response. In precision cardiology, cardiac digital twins are explored, especially in rhythm disorders, with potential support for procedural planning and individualized predictions [78].

Integration of multimodal data into mechanistic and statistical models, amplified by the development of AI (including generative AI), may enable more dynamic simulations and real-time recommendations. However, major challenges remain regarding model personalization, clinical validation, computational resources, interoperability, and ethical governance [79,80].

In atrial fibrillation, atrial digital twins (particularly of the left atrium) can integrate structural, electrophysiological, and hemodynamic data to simulate arrhythmia behavior, therapeutic response, and thromboembolic risk. Applications include stroke risk prediction through computational fluid dynamics, in silico testing of antiarrhythmics, and virtual ablation planning. Nevertheless, scalability and prospective validation remain prerequisites for clinical translation [81]. Along the same line, virtual testing of amiodarone guided by a digital twin suggests the possibility of pre-estimating efficacy in high-risk post-ablation patients, opening a promising direction for precision therapy [82].

Overall, the discussed data support a convergent transition toward predictive cardiology, in which continuous monitoring (wearable, implantable, contactless), digital biomarkers, and AI are integrated into secure clinical ecosystems. However, large-scale translation depends on: (1) prospective validation in real-world conditions, (2) methodological standardization, (3) interoperability and integration into clinical workflows, (4) data explainability and ethical governance, and (5) digital equity, ensuring that benefits are distributed without amplifying disparities.

Clinical benefits and impact on the healthcare system

The integration of digital technologies in cardiology generates significant clinical benefits, with a direct impact on patient outcomes and the organization of healthcare systems. Continuous monitoring of physiological parameters enables early diagnosis and timely identification of clinical deterioration, facilitating rapid intervention and reducing the risk of severe complications. At the same time, longitudinal analysis of individual data supports personalized prevention through dynamic risk stratification and adaptation of therapeutic interventions to each patient's profile. The implementation of remote monitoring and early warning systems contributes to the reduction of hospitalizations and readmissions, particularly in heart failure, where early interventions can prevent decompensation. Moreover, telemedicine and remote care expand access to specialized services, improve continuity of care, and optimize interdisciplinary coordination. From a systemic perspective, these transformations may lead to economic efficiency by decreasing costs associated with avoidable hospital admissions and reallocating resources toward high-risk patients.

4. Limitations, risks, and ethical challenges

Despite its transformative potential, digital cardiology faces important limitations. A major concern is the insufficient clinical validation of some artificial intelligence algorithms, often developed on limited or non-representative datasets, which raises questions about the generalizability of results. At the same time, algorithmic bias may amplify existing inequalities among different population groups, highlighting the need for explicit equity strategies and performance auditing. Data protection and cybersecurity become essential in a context characterized by the continuous collection of sensitive information. Massive data flows may also generate informational overload for clinicians, increasing the risk of alarm fatigue and reducing decision-making efficiency. At the institutional level, regulatory and clinical responsibility challenges persist, including approval processes by authorities such as the FDA and EMA. Finally, patient acceptance—shaped by digital literacy, trust, and privacy concerns—remains a critical determinant of real-world implementation.

5. Future directions

The evolution of digital cardiology indicates a transition toward deeply integrated and predictive models of care. The development of continuous AI-guided cardiovascular prevention is emerging, based on dynamic, real-time risk assessment. In parallel, the integration of the digital twin concept promises personalized simulation of disease progression and treatment response, opening new perspectives for precision medicine. Another emerging field is real-time algorithm-guided therapies supported by continuous monitoring and adaptive predictive models. In interventional cardiology, augmented reality may improve procedural precision and the planning of complex interventions. At the macro-systemic level, the future belongs to integrated digital ecosystems linking patient–hospital–home, characterized by interoperability, data continuity, and hybrid models of care.

CONCLUSION

Digital cardiology is undergoing a profound transformation driven by the convergence of connected devices, digital biomarkers, telemedicine, and artificial intelligence. This evolution marks the shift from episodic monitoring to predictive and personalized medicine, with major potential to improve early diagnosis, prevention, and the efficiency of healthcare systems. However, sustainable implementation requires rigorous clinical validation, clear regulatory frameworks, ethical data governance, and true integration into clinical workflows. In this context, technology does not replace medical judgment but becomes the central infrastructure of the cardiology of the future—an anticipatory, connected, and deeply patient-centered cardiology.

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Authors' contribution

Conceptualization, S.S.T, I.D.F. ; methodology, I.D.F., C.N.D. ; resources, B-V.V., C.N.D.; writing—original draft preparation, S.S.T, I.D.F., B-V.V.; writing—review and editing, S.I.D., A.E.M. ; supervision, S.I.D., A.E.M.. All authors have read and agreed to the published version of the manuscript.

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Ethics approval and consent to participate

Not applicable.

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