OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Conventional and AI-Assisted Biomarkers for Early Detection of Cardiac Dysfunctions in Adolescents

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ABSTRACT

Cardiac dysfunction in adolescents can remain silent or have subclinical signs, making early detection challenging. In recent years, the incidence and prevalence of cardiac-related abnormalities have increased drastically, particularly with rising obesity, sedentary behaviors, high-calorie diets, and psychosocial stressors. Cardiac dysfunction can involve abnormalities in the heart's structure, function, or electrical activity. They may result from genetic, inflammatory, metabolic, congenital, or acquired causes.

Clinical manifestations of cardiac dysfunction include abnormal heart rate, elevated blood pressure, heart murmurs, reduced exercise tolerance, and other cardiovascular symptoms. Conventionally, routine screening includes blood pressure, BMI, family history, and symptom review, with further investigations such as ECG or echocardiography done when required. However, these tests provide a glimpse of cardiovascular health at a particular point, and early or subclinical abnormalities may go unnoticed.

Non-conventional methods, such as wearable technologies and AI-assisted approaches, can help identify subtle patterns that are not clearly visible in single clinical measurements. Instead of diagnosing cardiac dysfunction independently, the non-conventional approaches can support earlier risk prediction and timely monitoring. This article reviews non-conventional practices to detect cardiac dysfunction and examines how AI-assisted strategies can provide additional support for early detection and prevention of adverse cardiac events in adolescents.

INTRODUCTION

In a recent global study, 3–5% of adolescents have hypertension, with higher rates observed particularly in obese populations (Genovesi, Volpe, & Agnoletti, 2026; Ruan, Zhu, & Wang, 2025). Recent data have shown that these trends have increased drastically by almost 33% in the past few decades (De Blas-Zapata, Sastre-Albiach, Baixauli-López, López-Ruiz, & Alvarez-Pitti, 2025; Ruan et al., 2025). Moreover, longitudinal studies have proven that these cardiac dysfunctions may exacerbate the risk of cardiac morbidity in adulthood (De Blas-Zapata et al., 2025; Ruan et al., 2025). The recent increase in the incidence and prevalence of cardiac dysfunctions reflects broader societal changes, such as sedentary behaviours, high-calorie diets, and psychosocial stressors (De Blas-Zapata et al., 2025; Ruan et al., 2025). Latest imaging-based studies reveal that subclinical cardiac abnormalities, such as left ventricular

hypertrophy and impaired myocardial strain, have been increasingly detected in adolescents without overt symptoms (De Blas-Zapata et al., 2025).

Cardiac dysfunction is associated with an abnormality where the heart cannot effectively pump blood. In recent times, an overwhelming number of cardiac-associated abnormalities have been found in adolescents (Boddu, Giannini, & Marcovecchio, 2025). Broadly, they are sub-classified into different categories: pump dysfunction, structural heart disease, electrical dysfunction, and metabolic and lifestyle-driven dysfunction (Boddu et al., 2025). Each subtype demonstrates a unique disease pattern, but all share similar risk factors. Traditional risk factors may include multiple causes; amongst them, obesity and lack of exercise are the leading and most prominent identifiers (Boddu et al., 2025).

Recent studies suggest that these risk factors rarely occur in isolation; instead, they always cluster and interact, thereby amplifying cardiovascular risks for disease development (Chanchlani, Brady, Kruger, Sinha, & Health, 2026; Lloyd-Jones, 2022). For instance, adolescents with obesity will have a greater chance of exhibiting underlying abnormalities such as hypertension, dyslipidemia, and early myocardial dysfunction (Chanchlani et al., 2026; Lloyd-Jones, 2022). Early prevention of cardiac dysfunction in adolescents is a realistic goal with current knowledge to limit the short- and long-term cardiac and systemic complications associated with unwanted cardiac events.

This review article reflects conventional and non-conventional approaches to identify and limit cardiac abnormalities amongst adolescents (Figure 1). Biomarkers are one of the crucial aspects in figuring out what is out of the ordinary (Zrinski Topic & Lenicek Krleza, 2025). These biomarkers can be used to diagnose cardiac dysfunction long before the effects take hold. At present, the current literature related to cardiac dysfunction and its associated abnormalities is vast and unpredictable; changes must be made on a personal, community, and national level to limit complications (Lloyd-Jones, 2022). Moreover, this article provides details about both conventional and non-conventional practices to detect cardiac dysfunction and how AI-assisted approaches can provide additional aid for early detection and prevention of unwanted cardiac events amongst the young population.

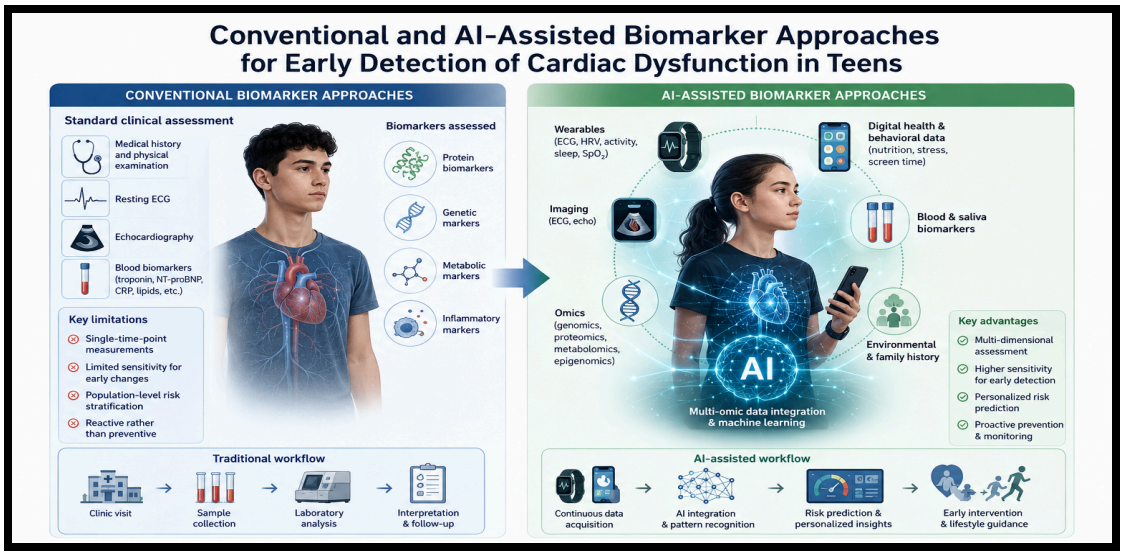


Figure 1: Graphical representation of the role of conventional and AI-assisted biomarker approaches, which can be used for the early detection, evaluation, and monitoring of cardiac dysfunction amongst adolescents. The image was created with BioRender (https://www.biorender.com), with assistance from ChatGPT (GPT-5.5).

LITERATURE REVIEW METHODOLOGY

The narrative review examined literature based on conventional and AI-assisted biomarkers for early detection of cardiac dysfunction in adolescents. Electronic databases, such as Google Scholar, PubMed, Scopus and Web of Science, were searched for studies published between January 2010 and August 2026. MESH terms such as "artificial intelligence," "cardiac dysfunction," "cardiovascular disease," "cardiac biomarkers," "early detection," "digital biomarkers," "adolescent," and related combinations were searched in different databases.

English-language original studies, systematic and narrative reviews, meta-analyses, and relevant clinical guidelines addressing adolescents, biomarkers, or AI-assisted cardiovascular detection were identified. However, studies focusing on adult populations, unrelated cardiovascular outcomes, and non-biomarker applications were excluded from further analysis and critical evaluation for the current review

CLINICAL MANIFESTATIONS OF DIFFERENT CARDIAC DYSFUNCTIONS AMONGST ADOLOSCENTS

Cardiac dysfunction in adolescents can occur through several mechanisms, including pump dysfunction, structural heart disease, electrical dysfunction, metabolic or lifestyle-associated dysfunction, and inflammatory or genetic causes (Hertiš Petek, Petek, Močnik, & Marčun Varda, 2022). Although these

categories are described separately, they may overlap in clinical practice and contribute collectively to impaired cardiac performance.

Pump Dysfunction

Pump dysfunction occurs when the heart muscles become too weak to squeeze blood out effectively, or the heart gets too stiff, resulting in the inability to fill with blood (Boddu et al., 2025). It is referred to as the mechanical failure of the heart and typical signs include shortness of breath, oedema of the ankles, fatigue, and rapid or irregular heartbeat.

Structural Heart Disease

Structural heart disease refers to abnormalities in the physical structures of the heart, including the valves, chambers, and walls (Masenga & Kirabo, 2023). These abnormalities may be present from birth or acquired later in life due to injury, infection, etc. (Masenga & Kirabo, 2023). Some congenital abnormalities include Atrial Septal Defects (ASD), Ventricular Septal Defects (VSD), or Patent Foramen Ovale (PFO) (Masenga & Kirabo, 2023).

Electrical Dysfunction

Electrical Dysfunction, or cardiac arrhythmia, is when the heart's electrical wiring, or the conduction system is disturbed (De Blas-Zapata et al., 2025; Ruan et al., 2025). The two conditions associated with Electrical Dysfunction are tachycardia, where the heart beats too fast, and bradycardia, where the heart beats too slowly (De Blas-Zapata et al., 2025; Ruan et al., 2025). Further, these conditions are closely related to two subtypes of Electrical Dysfunction: Atrial Fibrillation (AFib) and Ventricular Fibrillation (VFib) (Ruan et al., 2025).

Metabolic and Lifestyle-Driven Cardiac Dysfunction

Metabolic and lifestyle-driven cardiac dysfunction, also known as CKM syndrome (Cardiovascular-Kidney-Metabolic syndrome), is a condition where poor lifestyle choices trigger risk factors such as obesity, systemic inflammation, and insulin resistance, causing a long-term strain on the cardiovascular system (Boddu et al., 2025). These metabolic issues result in the stiffening of the heart, which increases the risk of heart failure (Boddu et al., 2025). The result of these neglected habitual choices is shortness of breath, unexplained fatigue, heart palpitations, and elevated blood pressure (Boddu et al., 2025).

Inflammatory and Genetic Cardiac Dysfunction

Inflammatory and genetic cardiac dysfunction refers to heart problems that arise due to genetic factors and immune-mediated responses, which can interact to cause heart muscle weakening and electrical abnormalities (Merlo et al., 2025). Genetic mutations can make the heart more vulnerable to inflammation and environmental triggers, which may lead to arrhythmias, cardiac dysfunction, and, in severe cases, heart failure (Merlo et al., 2025).

RISK FACTORS ASSOCIATED WITH CARDIAC DYSFUNCTION IN ADOLOSCENTS

Cardiac dysfunction is influenced by a list of controllable and uncontrollable risk factors. Uncontrollable risk factors include family history of cardiac abnormalities, and genetic predisposition to diabetes and hypertension (Parizad, Batta, & Hatwal, 2025). Although these risk factors cannot be changed, they can help to evaluate which individuals are at high risk of cardiac diseases (Parizad et al., 2025). In contrast, controllable risk factors are behaviour based and depend on the adolescent. These factors include lack of physical activity, unhealthy dietary patterns and psychological stress. In recent years, controllable risk factors such as obesity and lack of exercise are rising at an alarming rate in adolescents (Huang, Sulek, & Stinson, 2025). Obesity, in particular, plays a central role in increasing cardiac load by promoting insulin resistance and triggering systemic inflammation (Huang et al., 2025). These risk factors may contribute to early development of cardiac dysfunction in young adults (Huang et al., 2025). Furthermore, the risk factors tend to cluster together, meaning that adolescents may exhibit multiple risk factors at the same time, thereby amplifying cardiovascular risk. Many of these risk factors are addressable, highlighting the importance of early lifestyle changes and preventive strategies to improve long-term cardiac health.

CLINICAL MANIFESTATIONS IN ADOLESCENTS

Cardiac dysfunction displays a variety of symptoms in adolescents similar to adults depending on the underlying cause and the severity (Figure 2). Common clinical manifestations of cardiac abnormalities include peripheral oedema, which is the swelling of the ankles or feet, and rapid weight gain (Mannarino et al., 2022). Health care professionals can assess these signs and use them to diagnose a potential problem in a patient.

During a routine checkup, signs such as abnormal heart rate, abnormal blood pressure, and a heart murmur may indicate that the structural aspect of the heart is malfunctioning (Mannarino et al., 2022). Clinically, the signs for cardiac dysfunction are limited, with only seven major signs that can indicate heart complications (Mannarino et al., 2022). These changes may also occur in other medical conditions, so the room for early detection is very minimal (Mannarino et al., 2022). Most children and adolescents overlook the initial signs, and as a result, heart issues have had a steady growth rate for the past few decades (Mannarino et al., 2022).

Clinical detection is crucial, and identifying signs specifically related to the heart adds another layer of complication. Seven possible signs related to the identification of cardiac issues include: (i) abnormal heart rate which can mean irregular heart rhythm and an affected tachycardia, (ii) elevated blood pressure considering the age and weight, (iii) systolic or diastolic heart murmur which can indicate structural damage to the heart, (iv) poor perfusion which is reduced blood flow to organs and tissues meaning when the lungs have weak peripheral pulses and delayed capillary refill alongside other symptoms, (v) peripheral oedema which is the swelling of the ankle and foot, (vi) jugular venous distension which is when the jugular vein on the neck is popping out of the skin suggesting increased pressure, and lastly (vii) poor growth or rapid weight gain which can be a result of poor metabolism (Mannarino et al., 2022;

McGinn, Casey, Watson, & Morrison, 2023; Merlo et al., 2025) (Figure 2). Therefore, the recognition of unusual cardiovascular signs followed by appropriate clinical assessment is important for early intervention.

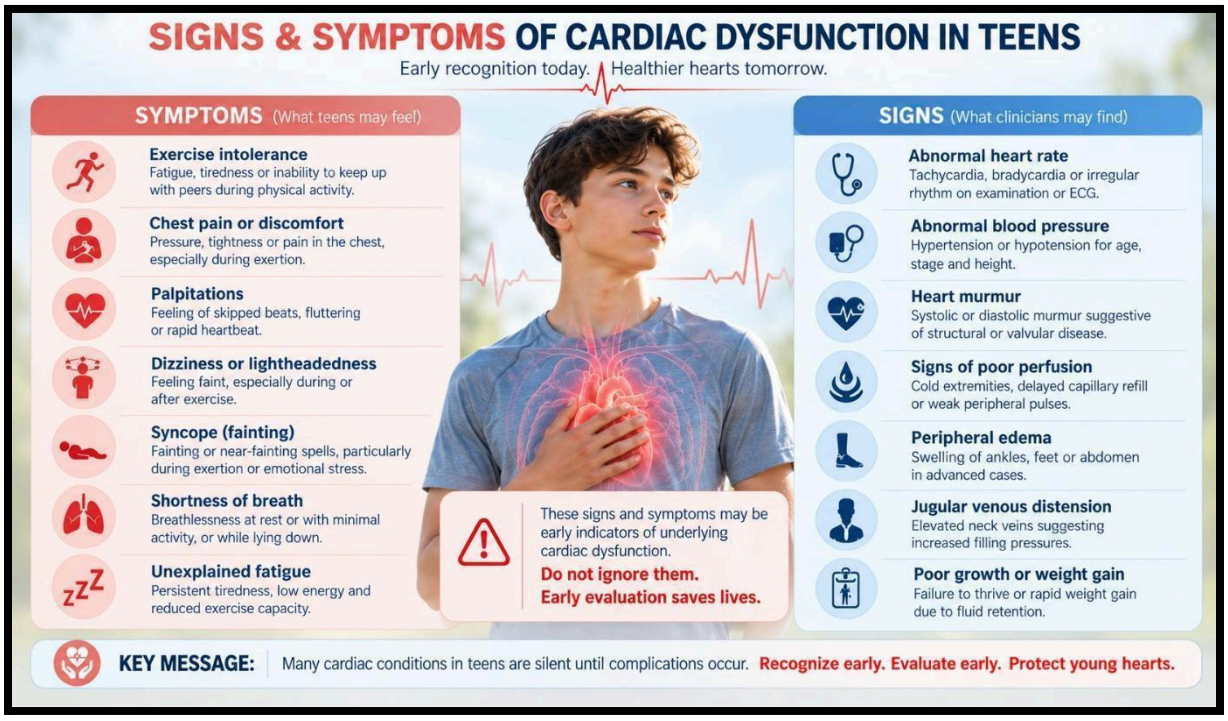


Figure 2: Clinical manifestations of cardiac dysfunction amongst teenagers range from mild symptoms to serious and life-threatening complications which impair normal growth and development, affecting the quality of life. The image was created with BioRender (https://www.biorender.com), with assistance from ChatGPT (GPT-5.5).

CONVENTIONAL APPROACHES FOR EARLY DETECTION AND SCREENING

Adolescent cardiac dysfunction is often silent, and early detection and prevention is crucial to minimizing the short-term and long-term complications. While early detection is crucial and there are numerous conventional methods, detection is often made too late to prevent complications (A. S. John, Jackson, & Moons, 2022). Some conventional early detection techniques used include blood pressure, ECG, genetic testing, fasting lipids and glucose/A1c (A. S. John et al., 2022). Tests such as blood pressure and BMI are general tests which can be taken at any time to detect abnormalities (A. S. John et al., 2022). It also gives an idea of whether an individual is susceptible to cardiac dysfunction. If abnormalities have been established, the next steps are to take tests such as ECG, genetic testing, fasting lipids and glucose/A1c to assess whether cardiovascular involvement or associated metabolic risk is present (A. S. John et al.,

2022). Biomarkers are another crucial conventional approach that help in identifying biological changes indicative of a cardiac injury or cardiovascular risk. These biomarkers include Troponin, NT-proBNP/BNP, Lipids, glucose, HbA1c, and CRP or other inflammatory markers (Babb de Villiers, Plans-Beriso, & Erady, 2025; R. V. John, 2022). These biomarkers help understand information about the different components of cardiovascular health that might further help in the diagnosis of cardiac dysfunction (Babb de Villiers et al., 2025). Troponin levels can be assessed to find possible myocardial injury, while NT-proBNP/BNP tests can indicate heart wall stress and are commonly associated with heart failure physiology (Babb de Villiers et al., 2025; Bohn & Adeli, 2023; R. V. John, 2022).

Lipids, glucose, and HbA1c can help detect possible cardiometabolic risk factors that may contribute to future cardiac dysfunction (R. V. John, 2022). CRP and other inflammatory markers can provide information about metabolic inflammation. Each biomarker can help detect a particular abnormality, but is not indicative of the overall picture (Babb de Villiers et al., 2025; Bohn & Adeli, 2023; R. V. John, 2022). The major limitation is that a single marker may lack sufficient specificity when interpreted alone (Babb de Villiers et al., 2025; Bohn & Adeli, 2023; R. V. John, 2022). Assessing multiple biomarkers requires numerous tests and takes a lot of time to conclude (Babb de Villiers et al., 2025; Bohn & Adeli, 2023; R. V. John, 2022). Therefore, combining biomarker analysis with clinical, physiological, and imaging data with the help of AI may potentially provide a more complete and quicker assessment of cardiac risk.

Adolescents who also need closer and continuous assessment include patients who exhibit the symptoms of exertional chest pain, dyspnoea, palpitations, syncope, and exercise intolerance (Chhabria, LeBron, Ronis, & Batt, 2024). They are at high risk for cardiac dysfunction, as are patients with a family history of sudden death, cardiomyopathy, inherited arrhythmia, and premature CVD (Chhabria et al., 2024). Other high-risk individuals include people with risk factors such as obesity, hypertension, diabetes, etc. and individuals with known diseases such as congenital heart disease, a history of myocarditis, or cardiomyopathy (Chhabria et al., 2024). Early detection is crucial, but it is even more crucial to test patients who require immediate attention to prevent complications. Therefore, early detection should follow a risk-based screening approach where routine assessment is combined with advanced testing.

NON_CONVENTIONAL APPROACHES FOR EARLY DETECTION AND MANAGEMENT OF CARDIAC RELATED ADVERSE EVENTS

It is important to utilize non-conventional approaches to prevent and identify cardiac dysfunction early in adolescents. Traditional screening is based on periodic clinical assessment using family history, blood pressure, ECG, echocardiography, and lab tests (Hampl, 2023; Mayourian, 2025). In comparison, non-conventional approaches use longitudinal measures such as wearable physiology, app behaviour, home blood pressure, digital biomarkers, and AI risk models (Leone, O'Sullivan, & Bravo-Jaimes, 2025) (Figure 3). With the help of AI risk models, patients at increased risk may potentially be identified earlier, allowing closer monitoring and preventive intervention (Leone et al., 2025). Although these non-conventional approaches can be used for both adults and adolescents, the willingness to adopt AI and

tech based interventions is higher among young adults and the ability to assimilate long term data through AI enabled data collection can make a significant impact in adolescents when compared to older patients. However, AI should be integrated into supervised care pathways rather than used as a standalone diagnostic tool. For example, ECG and echocardiogram data are important for clinical evaluation, while AI can assist with creating risk scores, pattern identification, and trend detection that may not be immediately apparent (Leone et al., 2025). With the help of AI and its pattern recognition capabilities, clinical action can be taken earlier to prevent potential cardiac dysfunction and improve quality of life (Lee, Croon, & Lee, 2026). Therefore, when appropriately validated and used alongside clinical judgement, AI may increase the efficiency and accuracy of cardiac abnormality detection and risk assessment.

AI-assisted ECG

Examining an ECG test can provide important information on what abnormalities are present, but some subtle signals may be missed during routine interpretation (Lee et al., 2026). This is where AI-assisted ECG can be useful to detect patterns that are difficult to recognize visually (Lee et al., 2026). These abnormalities may include irregular arrhythmia patterns, conduction abnormalities, inherited/channelopathy risk, potential ventricular dysfunction, and findings that may indicate a need for echocardiography or specialist review (Lee et al., 2026). This is important because early recognition of subtle ECG changes might prompt further investigation before significant clinical dysfunction occurs (Lee et al., 2026). However, AI should remain as an assisting tool rather than replacing expert clinicians (Lee et al., 2026). So appropriate guardrails need to be ensured, including pediatric validation, age/sex/body-size calibration so the data is accurate, false-positive management, and clinician-in-the-loop decision-making.

AI-assisted echocardiography

AI can also be incorporated in tests such as echocardiography. It can assist with automated identification of the chambers and measurement of ventricular dimensions and volume (Nguyen et al., 2022). AI may also support strain analysis, an echo method that measures myocardial deformation and can identify subtle changes in cardiac function before a clear indication of dysfunction appears in the conventional measures. AI can also help perform image quality checks and help standardize measurements across operators and centres (Nguyen et al., 2022). Finally, AI-based models can integrate echocardiographic findings and clinical variables to improve risk prediction and prognosis (Nguyen et al., 2022). Therefore, one of its potential advantages is the earlier and consistent detection of myocardial dysfunction that may require closer follow-up.

AI assisted wearable and smart devices

Wearables and smart devices extend cardiac monitoring beyond clinic visits. They can help detect trends for irregularities such as tachycardia burden, activity intolerance, sleep disruption, and abnormal recovery patterns (Hughes, Taylor, Morris, & Brittain, 2026). For adolescents considered at higher cardiovascular risk, regular and consistent monitoring can reveal changes that are not captured during a single clinic visit (Hughes et al., 2026). Monitoring with wearables provides valuable longitudinal data that can help track

abnormalities and identify unusual patterns (Hughes et al., 2026). This can help determine whether further investigation is required. But wearable findings should be considered for screening and monitoring purposes rather than diagnostics because device accuracy and types of measurements vary across devices.

Remote and Tele-monitoring

Hypertension is an important modifiable cardiovascular risk factor in adolescents, making telemonitoring and regular remote blood pressure monitoring potentially useful (Hardon, Van Kerkhof, Bartelds, Kammeraad, & Van Deutekom, 2025). Checking blood pressure regularly can help detect masked/white-coat patterns, monitor treatment response, reduce visit burden, and support earlier lifestyle or drug intervention (Ho et al., 2025). Remote monitoring can also be combined with digital health interventions that support cardiovascular risk reduction (Nguyen et al., 2022). For example, digital therapeutics can give guidance on nutrition coaching, which helps reduce ultra-processed foods and support healthier lipid and glucose profiles (Ho et al., 2025). Another benefit of digital therapeutics is activity reminders, which help reduce sedentary behavior and encourage daily movement (Ho et al., 2025). Medication reminders can also help patients take prescribed medicines consistently. In addition, symptom diaries can help track symptoms such as palpitations, syncope, chest pain, and fatigue patterns, providing clinicians with longitudinal information that may help guide further assessment.

Large-Language models-assisted devices

Another emerging digital approach is the use of LLMs and conversational AI (Sethi, Patel, & Kaka, 2022). These platforms have potential as supportive tools rather than replacements for trained healthcare professionals (Armoundas, Narayan, & Arnett, 2024; Sethi et al., 2022). They can help explain diagnoses, treatments, and warning signs in simpler language and can also provide personalized reminders and motivational support when incorporated into clinically supervised protocols (Armoundas et al., 2024; Ferreira Santos, Ladeiras-Lopes, Leite, & Dores, 2025; Sethi et al., 2022). When integrated into healthcare systems, they can act as a portal to access and understand medical records (Ferreira Santos et al., 2025; Sethi et al., 2022). However, LLMs can hallucinate and generate inaccurate information, show bias, or provide advice without sufficient clinical context (Armoundas et al., 2024; Ferreira Santos et al., 2025; Sethi et al., 2022). Therefore, their use requires careful validation, clinician oversight, and regulation (Armoundas et al., 2024; Ferreira Santos et al., 2025). Their main value can be harnessed through integration with wearables, smart devices, and digital therapeutics, crucial for early detection of cardiac dysfunction and prevention strategies.

AI-assisted biomarkers

Instead of looking at each biomarker, AI can be useful for integrating multiple types of information for a broader assessment of cardiac risk. Biofluid markers measured from blood include troponin, NT-proBNP, lipids, and glucose, while salivary markers such as exploratory troponin, NT-proBNP, and cortisol are still being explored as less invasive alternatives to measure risk (Fang et al., 2026) (Figure 3). Alongside these biomarkers, the physiological measurements of an individual can also provide useful information (Fang et al., 2026). These may include ECGs, HRVs, PPGs, blood pressure, measured sleep, activity, exercise recovery, and symptom diaries from wearables or apps (Fang et al., 2026).

These measurements can be used with biofluid markers, and AI models can identify the relationship between the different data types that are difficult to recognise when considered individually, thereby providing more accurate calculations. Clinical Context is another important component of measurement for risk calculation (Fang et al., 2026). These include controllable variables such as exercise load and medication, social environment, and body size, while uncontrollable variables include age, sex, puberty, obesity, and family history (Fang et al., 2026). Both controllable and uncontrollable variables can provide context to help decide whether an individual is at high risk for cardiac dysfunction (Fang et al., 2026).

Another biomarker that can be analyzed is imaging data. Imaging techniques can include echo strain, Left Ventricular mass, chamber size, ejection fraction, congenital/anatomic features, and longitudinal imaging change (Fang et al., 2026). Individually, these four types of biomarkers (clinical context, biofluids, physiology, and imaging) provide only fragments of the overall risk profile (Fang et al., 2026). But with the help of AI-based pattern recognition, these data may be integrated into a more comprehensive model for risk estimation of cardiac dysfunction.

Multi-omics biomarkers

Multi-omics biomarkers are still largely a part of discovery but have huge potential for the detection of cardiac dysfunction. Multi-omics approaches include genomics, transcriptomics, proteomics, metabolomics, and lipidomics (Ananthamohan et al., 2025). Genomics examines DNA sequence and genetic variation and may help identify adolescents at a higher risk of inherited cardiac myopathy, channelopathy, and polygenic cardiometabolic disease (Ananthamohan et al., 2025). Transcriptomics examines RNA expression and may provide information about pathways associated with myocardial stress, inflammation, and cardiac remodelling (Ananthamohan et al., 2025).

Another multi-omics approach is proteomics, which can help identify changes in proteins involved in inflammation, fibrosis, and endothelial and myocardial stress pathways. Metabolomics examines small molecules involved in cellular metabolism and may reveal patterns of insulin resistance, mitochondrial stress, and altered energy metabolism (Ananthamohan et al., 2025). Lipidomics focuses on lipids and may help in early detection of cardiometabolic risk signatures, particularly in adolescent obesity (Ananthamohan et al., 2025). Each one of these multi-omics approaches captures a different aspect of cardiovascular biology; their combined analysis can provide a more complete picture.

Saliva

Cardiac troponins and BNP/NT-proBNP are established circulating biomarkers of myocardial injury and cardiac dysfunction (Tran et al., 2025; Zrinski Topic & Lenicek Krleza, 2025). Salivary biomarkers demonstrate a promising non-invasive approach for assessing cardiovascular health; however, their clinical relevance amongst adolescents remains exploratory.

Latest evidence has demonstrated important limitations: the lack of concordance between salivary and serum cardiac troponin concentrations (Vasileva et al., 2024). Moreover, some paediatric studies have

established that salivary molecular markers can be associated with cardiovascular parameters, but these findings require validation in larger, diverse cohorts (Vasileva et al., 2024). At present, salivary biomarkers cannot be considered suitable for routine school, community and population-level cardiovascular screening. Prospective validation, assay standardization, and age-specific reference ranges must support their future roles for non-invasive cardiovascular risk assessment and monitoring among high-risk individuals (Vasileva et al., 2024).

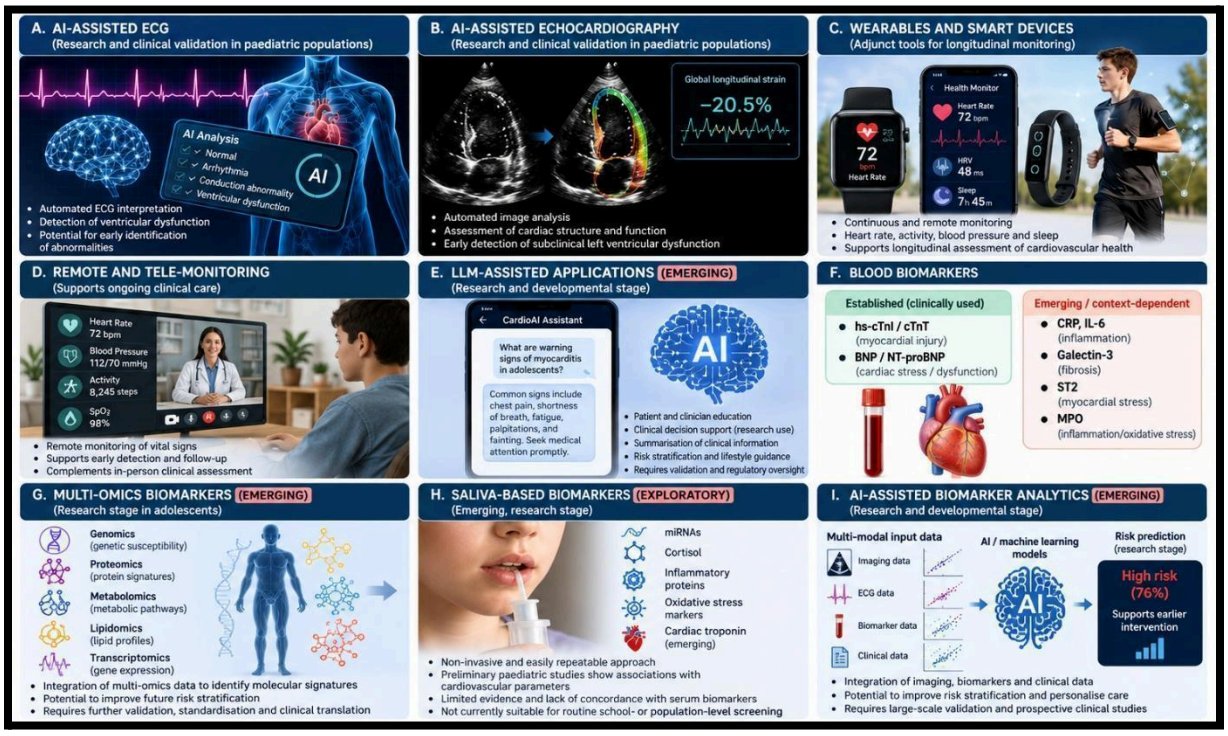


Figure 3: Non-conventional approaches such as AI-assisted ECG, AI-assisted echocardiography, wearable and smart devices, remote and tele-monitoring, large-language model-assisted devices, biomarkers, AI-assisted biomarkers, multi-omics biomarkers, and saliva can be used for early diagnosis and monitoring of diverse cardiovascular events amongst adolescents. The image was created with BioRender (https://www.biorender.com), with assistance from ChatGPT (GPT-5.5).

FUTURE DIRECTIVES

Future work should focus on validating adolescent-specific biomarker thresholds, integrating AI-derived digital phenotypes, and determining whether earlier detection changes clinical trajectories before heart failure, arrhythmia, or stroke emerges (Armoundas et al., 2024). This is particularly important because cardiac dysfunction in adolescents is often subclinical and single measurements can miss gradual changes over time. Biomarkers should therefore be interpreted according to age, pubertal stage, exercise timing, and relevant comorbidities rather than using a single threshold across all adolescents (Babb de Villiers et

al., 2025). Alongside this reframing, AI can be incorporated to provide further assistance by integrating different variables to identify condition-specific patterns (Armoundas et al., 2024). The long-term goal should be to develop a staged pathway in which adolescents are screened, risk-stratified, clinically confirmed, and treated when necessary, including in low-cost screening environments such as schools and community programs.

Future biomarker research should be multimarker, longitudinal, and clinically interpretable. Rather than relying on single measurements, studies should determine how established blood biomarkers such as hs-cTnI/T and NT-proBNP/BNP change over time and whether a combination of markers provides better detection (R. V. John, 2022; Zrinski Topic & Lenicek Krleza, 2025). Non-invasive biomarkers, such as saliva, represent a potential scalable screening frontier because sampling is non-invasive, repeatable, and suitable for community-based settings (Tran et al., 2025). They can potentially be used for population-scale screening and have the possibility of becoming a regular screening practice. Salivary biomarkers require analytical validation, stability testing, and cardiac-specific cut-offs (Vasileva et al., 2024). Multi-omics approaches such as genomics, proteomics, and metabolomics can also be integrated with AI for risk calculation (Nordestgaard, Wolford, & de Gonzalo-Calvo, 2025). Future studies should determine whether the combined approaches reduce missed subclinical disease without creating unnecessary false positive referrals.

Future work should also focus on developing integrated risk dashboards that merge laboratory biomarkers, salivary measurements, ECG, echocardiography, and wearable data trajectories into a single explainable adolescent cardiac-risk profile (Nguyen et al., 2022). AI-ECG can help detect patterns associated with ventricular dysfunction, cardiomyopathy, arrhythmia risk, and structural disease, while AI-echocardiography can help automate segmentation, strain analysis, and functional quantification. Wearables can provide longitudinal physiological data that may reveal gradual changes between clinical visits. The main future challenge is not simply collecting more data, but understanding how the different data modalities can be combined, weighted, and analyzed reliably. Such models will require adolescent-specific validations and clinical thresholds to guide screening and treatment.

CONCLUSION

Cardiac dysfunction in adolescents can stay silent and should be considered as a continuum in which early risk prediction may help prevent progression and development to severe cardiac issues. Conventional biomarkers can provide information about myocardial injury, cardiac wall stretch and cardiometabolic risk, but their interpretation in adolescents can be influenced by puberty, exercise, sex differences, and limitations in reference intervals for some markers. Individual biomarkers only capture a fragment of the overall clinical picture, making early or subclinical abnormalities difficult to identify.

AI-assisted and other non-conventional approaches can help address this limitation by integrating information from blood, saliva, ECG, echocardiography, wearable, and multi-omics data to identify hidden patterns or changing trajectories before apparent symptoms or structural disease emerge. AI could

therefore support clinicians in risk stratification, early detection, and the development of treatment strategies. But AI should not be used as a sole diagnostic tool but instead remain a tool that is supervised by clinicians.

This field now needs prospective validation, equity-sensitive implementation, and outcome-based trials showing whether these approaches actually reduce the number of missed cases, unnecessary referrals, and cardiac complications, rather than simply improving prediction metrics. Emerging biomarkers, such as salivary biomarkers and multi-omics, can expand early risk assessment, but they require validation before routine clinical use. The value of AI will depend on how effectively it supports, rather than replaces, clinical expertise and improves early identification of cardiovascular risk in adolescents.

LIST OF ABBREVIATIONS

ACE-inhibitors Angiotensin-Converting Enzyme inhibitors
AFib Atrial Fibrillation
AI Artificial Intelligence
ASD Atrial Septal Defects
BMI Body Mass Index
CKM syndrome Cardiovascular-Kidney-Metabolic syndrome
CRP C-reactive protein
CVD Cardiovascular Disease
DNA Deoxyribonucleic Acid
ECG Electrocardiogram
HRV Heart Rate Variability
ICD Implantable Cardioverter-Defibrillator
LLM Large Language Model
PFO Patent Foramen Ovale
PPG photoplethysmography
SVT Supraventricular Tachycardia
RNA Ribonucleic Acid
VFib Ventricular Fibrillation
VSD Ventricular Septal Defects

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