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EMERGING FRONTIERS IN CARDIOVASCULAR DIAGNOSTICS: A LITERATURE REVIEW

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ABSTRACT
Background: The cardiovascular diagnostic landscape is rapidly evolving, with novel and advanced techniques and technologies continually emerging. Detection, monitoring, and management of cardiovascular diseases (CVDs) are quickly changing, which are leading mortality cause globally. **Objective:** This review aims to provide a comprehensive and up-to-date assessment of the current cardiovascular diagnostic modalities. It seeks to elucidate novel and promising technologies, address their advantages, limitations, and potential integration into clinical practice. **Methods:** This literature review discusses the recent cardiovascular diagnostics which were obtained from various sources such as PubMed, EMBASE, and Web of Science for articles published in the last decade. **Results:** The review identified vital emerging frontiers in cardiovascular diagnosis, including advancements in multi-modal imaging (such as PET-MRI), novel biomarkers, artificial intelligence applications, and the growing utility of wearable and remote monitoring technologies. **Conclusion:** Emerging techniques integration inroutine clinical practice requires careful consideration of their advantages and potential for improving patient outcomes. The review highlights the pressing need for continued research and guideline to ensure these innovations realize their full potential for the future of cardiovascular medicine.
Keywords: *Cardiovascular, diagnostics, novel, technology*

INTRODUCTION

In the rapidly advancing healthcare field, cardiovascular diagnostics stands at the forefront. These diagnostic procedures are more than essential; they're a lifeline, providing in-depth insights into the heart's electrical activity, heartbeat rhythm, blood flow, and the heart's chambers and valves' functionality.[1] Heart diseases such as coronary artery disease, angina pectoris, arrhythmia, or cardiomyopathy are fatal and lead to sudden death.[2] The earliest diagnosing tools in cardiology were rudimentary yet groundbreaking for their time.The stethoscope invention in the early 19th century by René Laennec allowed physicians to auscultate heart sounds, diagnosing heart murmurs and abnormalities.[3] Subsequently, the development of the mercury-based sphygmomanometer in the mid-19th century by Samuel Siegfried Karl Ritter von Basch facilitated blood pressure measurement, aiding in the assessment of hypertension and cardiovascular health.[4]

Cardiovascular diseases (CVDs) constitute a global health crisis remaining the leading death cause worldwide. The statistics revealed an estimated 17.9 million people died from CVDs in 2019, representing 32% of all global deaths with CVD. Of 17.9 million deaths, 85% are attributed to heart attacks and strokes. Tragically, over three-quarters of CVD deaths occur in low- and middle-income countries.[8] In 2019, CVDs were responsible for 38% of the 17 million premature deaths (under 70) due to noncommunicable diseases[9]. The United States faces a similarly severe challenge with CVD, accounting for 928,741 deaths in 2020 alone. The direct and indirect costs of total CVD between 2018 and 2019 amounted to $407.3 billion, comprising $251.4 billion in direct costs and $155.9 billion in lost productivity/mortality.[10] A breakdown of the statistics reveals that, in the United States in 2020, coronary heart disease (CHD) was the leading cause of deaths attributable to CVD at 41.2%, followed by stroke at 17.3%, other CVD at 16.8%, high blood pressure at 12.9%, heart failure at 9.2%, and diseases of the arteries at 2.6%.[10-11]

The early 20th century witnessed the introduction of the electrocardiograph (ECG) by Willem Einthoven, which recorded the heart's electrical impulses and offered insights into cardiac rhythm and abnormalities.[5] As technology advanced, X-rays became valuable for visualizing the heart's size and shape, and angiography allowed visualization of coronary arteries to detect blockages. Cardiac catheterization, pioneered by Werner Forssmann in 1929, facilitated direct access

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to the heart's chambers for pressure measurements and blood sampling.[6] These early tools formed the foundation for the evolution of cardiology diagnostics, leading to advanced imaging techniques, noninvasive tests, and genetic diagnostics in modern cardiology practice. The conventional standard imaging techniques include echocardiogram via ultrasound, MRI, x-ray, computed tomography (CT), catheterization, and nuclear scans.[7] Behavioral risk factors such as tobacco use, unhealthy diet, obesity, physical inactivity, or over-alcohol consumption contribute to cardiac problems. It is essential to detect cardiovascular disease as early as possible so that management with counseling and medicines can begin.[8]

RESULTS

Latest Innovations in Cardiovascular Imaging Technique

Stress Echocardiography, from the 1980s, allowed evaluation under physical or chemical stress, though it also presented challenges in image quality. Lastly, 3D Echocardiography, emerging in the 2000s, revolutionized detailed structural assessments but relies heavily on advanced equipment and patient anatomy.[12]

Echocardiography, a mainstay in cardiac diagnostics, has experienced a paradigm shift over the past decade, advancing from traditional M-mode and 2-dimensional Echocardiography (2DE) to state-of-the-art 3-dimensional echocardiography (3DE).[13] With the integration of RT3DE in managing valvular heart diseases, the future of echocardiography promises even more refined diagnostics, set to become more ingrained in clinical guidelines and practice.[14] Three testing procedures in Echocardiography are Transthoracic Echo (TTE); external imaging of the heart, Transesophageal Echo (TEE); through the esophagus for a closer heart view, and Stress Echocardiography which evaluates heart function under stress.[15] Traditional 2DE had limitations, such as without 3D spatial coordinates and geometric assumptions.[16] Early comparisons established 3DE's superior accuracy in determining left ventricular volumes and ejection fractions versus conventional 2DE. Over the past 25 years, 3DE's utility in cardiovascular medicine expanded. Its versatility was unrivaled, from precise measurements of heart volumes, ejection fractions, and mass to pre-, intra-, and post-operative evaluations.[18] In the future, Anticipated enhancements in 3DE will hopefully comprise transducer technology improvements, superior temporal/spatial resolution, software advancements, and standardization across vendors. Fusion imaging, merging RT3DE with other modalities, is envisioned to elevate cardiac diagnostics further.[19]

Table 1. Echocardiography Techniques

Name	Year Introduced	Description	Clinical Relevance	Advantage	Limitations
Stress Echocardiography	1980s	TTE under physical/chemical stress	Evaluates cardiac function under stress; ischemia detection	Provides functional info; no radiation	Requires patient exertion or medication; image quality varies
3D Echocardiography	2000s	Three-dimensional echocardiographic imaging	Detailed structural assessment; valvular assessments	Enhanced visualization; aids in surgical planning	Requires advanced equipmen; quality depends on patient anatomy

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Table 2. Spectral CT (Computed Tomography) technologies

Name	Year	Description	Clinical Relevance	Advantage	Limitations
Total Body CT	1980	Scans entire body with CT	Detects cardiac and extracardiac anomalies; often used in trauma	Offers a comprehensive overview; detects unrelated potential issues	Higher radiation dose; is not always necessary for specific issues
Coronary CT	2004	Focuses on coronary arteries	Noninvasive coronary angiography; detects coronary artery disease	Can visualize coronary blockages non-invasively; less risk than catheter angiography	Requires contrast; can't quantify blockage severity as FFR
Iterative Reconstruction	2015	The improved image reconstruction method	Enhances CT image quality; used across all CT applications	Reduces radiation; offers more explicit images with fewer artifacts	Relies on modern hardware and software, which may slow down some scans
PCCT CT Perfusion	2015	Assesses blood flow in the myocardium	Evaluates areas of reduced blood flow, aiding in ischemia detection	Highlights viable vs. non-viable myocardium; functional assessment	Still relatively new; long-term data might be limited
Epicardial	2020	Focuses on epicardial region	Evaluates epicardial fat, a potential marker for coronary artery disease	New insights into cardiac risk via epicardial fat	Focused view; doesn't replace a comprehensive cardiac assessment

CT scanning was first introduced in 1970 for cardiac and thoracic imaging. However, its exposure to ionizing radiation remains a significant limitation. Total Body CT was introduced in the 1980s, which offered a comprehensive overview of potential issues, but its higher radiation dose raises concerns. PCCT CT Perfusion (2015) is a valuable method for assessing blood flow in the myocardium but requires further long-term data. Lastly, the Epicardial (2020) technique offers new insights into cardiac risk via epicardial fat but doesn't replace comprehensive cardiac assessment and maintains a more focused view.[20]

Spectral CT has emerged as a cutting-edge technique, providing superior contrast resolution, facilitating a more precise differentiation between various tissues and blood flow, and enhancing diagnostic accuracy. Coronary CT Angiography (CCTA) involves injecting a contrast dye followed by imaging to visualize the heart vessels. Coronary Computed Tomography Angiography (CCTA) has recently undergone significant advancements in its diagnostic precision and safety. Modern CCTA employs multidetector CT scanners, offering faster imaging with higher resolutions.[21] With the evolution of technology, radiation exposure has markedly decreased, making the process safer. Enhanced image reconstruction algorithms provide more explicit images by reducing artifacts. Dual-Energy CT scanning has emerged as a vital tool, utilizing two X-ray energy levels for better tissue differentiation and plaque visualization.[22] Another notable advancement is the Fractional Flow Reserve CT (FFR-CT), a noninvasive method measuring coronary arteries' blood flow and refining blockage assessments.[23] Furthermore, improvements in contrast agents ensure more precise imaging with minimal side effects. These collective advancements have made CCTA an indispensable and safer diagnostic tool in managing coronary artery disease. Most recent developments include dual-Energy Computed Tomography (DECT). DECT has revolutionized cardiothoracic imaging, with vendors devising unique hardware and software solutions for producing multi-energy datasets.[24] The infusion of novel post-processing algorithms and AI-driven data analysis augments the diagnostic yield of every CT scan, often without amplifying radiation exposure. In the future, the medical imaging domain will be on the brink of a revolution. The synergy of spectral

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dual-energy CT and the nascent photon-counting CT patients and healthcare providers are poised to immensely benefit from these avant-garde technologies in the forthcoming era, ensuring more gradually permeates routine clinical practice. Both comprehensive and safer cardiovascular diagnostics.[24]

Table 3. Cardiac MRI technologies

Name	Year	Description	Clinical Relevance	Advantage	Limitations
4D Flow MRI	2010	Visualizes blood flow in 3D plus time	Assesses hemodynamics; evaluates valvular heart disease, shunts, and vessel stenosis	Offers a comprehensive view of blood flow dynamics; can assess flow in any direction	Complex, requiring advanced software and post-processing
Fast Strain Imaging	2019	Evaluates myocardial tissue motion and deformation	Detects early myocardial diseases and dysfunction, useful in cardiomyopathies	Detects subtle myocardial changes; quick assessment	Still evolving; availability and standardization may vary
T1 and T2 Mapping	2013	Differentiates heart tissue properties	Evaluates myocardial fibrosis, inflammation, and edema; used in cardiomyopathies and myocarditis	Provides quantitative tissue characterization; helps in early disease detection	Interpretation varies with hardware; post-processing required
MR Fingerprinting	2015	Matches tissue signals to predefined patterns	Differentiates between various tissues and diseases, aiding precise diagnosis	Accurate tissue differentiation; might reduce scan times	Still new; consistency and standardization across sites may vary

Most recent advancement of MRI with 7T Scanners

Since Magnetic Resonance Imaging (MRI) 7T scanners launched offered the potential to acquire more precise and more detailed cardiovascular images than ever before. The elevated magnetic field strength of 7T scanners provides superior image clarity compared to their 1.5T and 3T counterparts and significantly enhanced image resolution.[25] The increased magnetic field strength facilitates improved tissue contrast, which is especially beneficial for distinguishing between healthy and diseased tissue in the heart and surrounding vasculature. Other advancements include Hybrid Imaging (PET-MRI and PET-CT), combining the strengths of two imaging methods, providing functional and anatomical information. In the future, these techniques will be frequently used globally. As the technology behind 7T MRI continues to advance and with the adoption of appropriate safety measures, it's anticipated that these scanners will play an increasingly vital role in the detailed examination and diagnosis of various cardiovascular conditions. This technology holds promise for advancing our understanding of heart diseases and guiding therapeutic interventions with precision.[26]

Catheter angiography

Coronary angiography is vital for visualizing blood flow in heart arteries to detect obstructions. This procedure traditionally involved catheter angiography, wherein a catheter introduces a dye into the coronary arteries.[27]. Digital Subtraction Angiography (DSA) eliminates the need for traditional film. Instead, the patient's pre- and post-contrast images are digitally subtracted, resulting in a more precise visualization of blood vessels. This reduces noise and offers better pictures of the coronary arteries. High-Definited Monitors in the angiography suites have significantly upgraded image clarity and resolution, providing minute detailing. Advanced software algorithms convert 2D photos into 3D coronary angiography, ensuring safer, more accurate, and more efficient procedures for patients.[28-29]

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Artificial Intelligence in Imaging

AI introduction in medical science groundbreaking revolution. Image processing has become hundred times faster and can assist in detecting abnormalities, potentially outperforming human interpretation in some instances. Recent advancements in AI have significantly impacted cardiology, especially in imaging. AI algorithms process medical images faster, detecting abnormalities and potentially outperforming human interpretation.[31] Automated image segmentation saves time and reduces errors in identifying heart structures. AI-based image enhancement improves visualization, even in compromised images. AI predictive models analyze patient data to accurately predict cardiovascular outcomes and identify high-risk patients. AI algorithms detect coronary artery disease non-invasively from coronary CT angiograms. They also see malignant arrhythmias from ECG data. Cardiac function assessment and risk stratification for heart failure benefit from AI-driven tools. Virtual cardiac biopsies assess myocardial tissue characteristics non-invasively. AI decision support systems integrate patient-specific data to offer evidence-based treatment recommendations. These advancements enhance diagnosis, early detection, and personalized care in cardiology, with AI poised to revolutionize the field further.[32]

Echocardiogram via Ultrasound

The field of Echocardiography has witnessed substantial advancements, aligning with the evolving requirements of cardiovascular healthcare. Modern 3D echocardiograms provide real-time, three-dimensional imaging, significantly enhancing the accuracy in identifying and assessing heart-related conditions. Techniques such as Intracardiac Echocardiogram (ICE) and Doppler echocardiogram have further refined the diagnostic process, enabling the exploration of various heart ailments through minimally invasive means. Additionally, integrating Electrocardiogram (ECG) with Echocardiography offers continuous monitoring of the heart's electrical activity. These advancements collectively underscore a future where cardiac care can be more targeted and proactive.[33]

Table 4. Advancement in Intravascular Imaging and Diagnostic Procedures

Name	Year Introduced	Description	Clinical Relevance	Advantages	Limitations
IVUS	1990s	Ultrasound imaging inside arteries	Visualizes plaque, assesses vessel walls	High-resolution, direct visualization of the arterial wall	Invasive; limited to larger vessels
MEG	The 1990s (for cardiac)	Magnetic field imaging	Emerging applications in cardiac fields	Noninvasive; no radiation	Limited cardiac applications; expensive
Cardiac Biopsy	1965 by R.T Bulloch	Direct tissue sampling from the heart	Diagnoses myocarditis, cardiomyopathies	Direct tissue assessment; definitive diagnosis for some conditions	Invasive; risk of complications; sampling error

Introduced in the 1990s, Intravascular Ultrasound (IVUS) has enabled detailed visualization of blood vessels, providing insights into various cardiovascular diseases. Magnetoencephalography (MEG), developed in the 1990s, has revolutionized noninvasive brain activity mapping.[34] In the 19^{th} century, the practice of Cardiac Biopsy, though a more established technique, continued to evolve with enhanced precision and efficiency in diagnosing heart diseases. These technological innovations collectively represent the forefront of cardiac and neurological care, improving diagnostic accuracy and patient outcomes.[35]

In recent years, Troponin Test, BNP/NT-proBNP, and hs-CRP have revolutionized cardiac care, offering enhanced early detection and management of heart-related conditions.[36]

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Table 5. Innovations in Cardiac Biomarker Testing

Name	Year Introduced	Description	Clinical Relevance	Advantage	Limitations
Troponin Test	1990s	Blood test for cardiac troponin	Indicates recent heart attack	Highly specific for cardiac muscle injury	May not detect minor injuries; timing critical
BNP/NT-proBNP	2000s	Blood test for heart failure markers	Indicates heart failure	Predictive of heart failure severity	Affected by other conditions like renal failure
hs-CRP	1990s	Blood test for inflammation marker	Cardiovascular disease risk assessment	Indicates inflammation; a potential predictor of CV risk	Non-specific; influenced by various factors

DISCUSSION

In echocardiography, innovations have transcended from the traditional 2-dimensional approach to state-of-the-art 3-dimensional Echocardiography (3DE), particularly real-time 3D Echocardiography (RT3DE). These breakthroughs facilitate an enhanced understanding of complex heart structures. Simultaneously, Computed Tomography (CT) technologies have matured from single-slice scans to multifaceted 64-slice CT imaging, enabling detailed plaque assessment and higher spatial resolution. Advancements in Cardiac Imaging and Diagnostics have significantly transformed the landscape of cardiovascular healthcare like CT scanning and MRI have evolved remarkably.[39] Cardiac MRI (CMRI) emerged in 1981, utilizing magnetic fields for detailed cardiac imaging. Fast Strain Imaging, T1 and T2 Mapping, and MR Fingerprinting have refined tissue motion assessment and tissue differentiation. 7T MRI Scanners, introduced recently, offer superior image clarity, aiding in precise diagnosis. Spectral CT, Dual-Energy CT, and Fractional Flow Reserve CT (FFR-CT) enhance accuracy and safety in coronary assessment. Nuclear Cardiac Imaging (SPECT, PET, MPI) and Optical Coherence Tomography (OCT) utilize radioisotopes and light for deeper insights into heart function. AI-driven image processing and wearable devices are revolutionizing diagnosis and monitoring, ushering in an era of more precise and proactive cardiac care.[38]

ETHICAL APPROVAL

There is no ethical approval.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

Conceptualization, Roy Novri Ramadhan and Dewi Ratna Sari; methodology, Muh Akram; software, Farhan Nurdiansyah; validation, Dewi Ratna Sari, Roy Novri Ramadhan, and Muh Akram; formal analysis, Roy Novri Ramadhan; investigation, Dewi Ratna Sari; resources, Muh Akram; data curation, Roy Novri Ramadhan; writing—original draft preparation, Roy Novri Ramadhan; writing—review and editing, Roy Novri Ramadhan; visualization, Muh Akram; supervision, Dewi Ratna Sari; project administration, Farhan Nurdiansyah; funding acquisition, Roy Novri Ramadhan

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