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# Cardiovascular Imaging in the Era of Precision Medicine: Insights from Advanced Technologies – A Narrative Review

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## ABSTRACT

**Background and Aims:** Cardiovascular diseases are responsible for a high mortality rate globally. Precision medicine has emerged as an essential tool for improving cardiovascular disease outcomes. In this context, using advanced imaging exams is fundamental in cardiovascular precision medicine, enabling more accurate diagnoses and customized treatments. This review aims to provide a concise review on how advanced cardiovascular imaging supports precision medicine, highlighting its benefits, challenges, and future directions.

**Methods:** A literature review was carried out using the Pubmed and Google Scholar databases, using search strategies that combined terms such as precision medicine, cardiovascular diseases, and imaging tests.

**Results:** More advanced analysis aimed at diagnosing and describing cardiovascular diseases in greater detail is made possible by tests such as cardiac computed tomography, cardiac magnetic resonance imaging, and cardiac positron emission tomography. In addition, the aggregation of imaging data with other omics data allows for more personalized treatment and a better description of patient profiles.

**Conclusion:** The use of advanced imaging tests is essential in cardiovascular precision medicine. Although there are still technical and ethical obstacles, it is essential that there is collaboration between health professionals, as well as investments in technology and education to better disseminate cardiovascular precision medicine and consequently promote improved patient outcomes.

**Abbreviations:** ACS, acute coronary syndromes; AI, artificial intelligence; BrP, Brugada phenocopy; BrS, Brugada syndrome; CAD, coronary artery disease; CI, confidence interval; CT, computed tomography; CCT, cardiac computed tomography; CCTA, coronary CT angiography; CMR, cardiovascular magnetic resonance; CNNs, convolutional neural networks; COURAGE, clinical results using aggressive drug evaluation and revascularization; CVD, cardiovascular diseases; DL, deep learning; DNNs, deep neural networks; ECG, electrocardiogram; ESC, European Society of Cardiology; FAME, fractional flow reserve versus angiography for multivessel evaluation; FFR, fractional flow reserve; HF, heart failure; HPP, hypophosphatasia; HR, hazard ratios; LMICs, low and middle-income countries; MI, myocardial infarction; ML, machine learning; MRI, magnetic resonance imaging; mSv, millisieverts; OMT, optimum medical treatment; PCI, percutaneous coronary procedures; PET, positron emission tomography; PROMISE, Prospective Multicenter Imaging Study for Evaluation of Chest Pain; Rb, Rubidium-82; SCOT-HEART, Scottish Computed Tomography of the HEART Trial; SR-DLR, super-resolution deep learning reconstruction.

## 1 | Introduction

Cardiovascular diseases (CVD) refer to a constellation of disorders that affect the heart and blood vessels. These include coronary artery disease (CAD), heart failure (HF), hypertension, cardiac arrhythmia, cerebrovascular disease, peripheral artery disease, malformation of vessels, and other conditions that may affect the circulatory system [1, 2]. Genetics, environment, and modifiable risk factors play a major part in the pathophysiology of these disorders. About one-third of all mortality worldwide in 2019 was attributable to CVD, which was the primary cause of 8.9 million deaths in women and a total of 9.6 million deaths in men, with more deaths occurring with increasing age [3].

Precision medicine represents an advanced strategy that utilizes information from an individual's genetic, environmental, and lifestyle factors to tailor medical management decisions. It entails defining diseases at a higher resolution through advanced genomic and other modern technologies such as imaging, allowing for more precise identification and targeting of specific subsets within diseases [4, 5].

In CVD only a few pathologies, such as Brugada Syndrome (BrS) have been found to have precise strategies that use genetic information to guide the diagnosis, treatment, and management of the disease [6]. Hence, utilizing advanced cardiovascular (CV) imaging, whether invasive or noninvasive, is crucial for achieving precision medicine. This will help in accurate diagnosis, personalized treatment planning, risk stratification, and guidance for interventional procedures, thereby enhancing therapeutic efficacy and outcomes for patients.

Thus, this review aims to provide a concise review on how advanced CV imaging supports precision medicine, highlighting its benefits, challenges, and future directions.

## 2 | Exploring Precision Medicine in CV Care

### 2.1 | Precision Medicine Overview

Precision medicine related to CVDs is defined as the personalized approach that takes into consideration an individual's genetics, lifestyle choices, and environmental exposures [7]. It aims to prevent and treat CVDs through healthy habits like physical activity, diet, smoking cessation, weight loss, and managing risk factors [8]. Also, one of the main advantages is that provides a targeted treatment. Targeted treatment combines genetic information, functional tests, and imaging results. Pharmacogenomics, a key pillar of targeted treatment, uses patients' clinical profiles and biological traits for customized diagnostics and therapy [9].

Studies highlight the benefits of tailored approaches in the diagnosis, treatment, and prevention of CV illnesses, improving patient outcomes. A 2015 Italian study analyzed personalized CVD prevention in over 12,000 high-risk patients followed by general practitioners for 5 years, achieving control of seven major risk factors [10]. Early identification and targeted treatment of high-risk individuals, along with new pharmacologic and nonpharmacologic interventions, reduced morbidity and mortality rates associated with CVDs. These findings underscore the role of personalized solutions in managing CV illnesses [11–13].

### 2.2 | How CV Imaging Supports Precision Medicine

Precision CV medicine relies on advanced imaging technologies like echocardiography, nuclear cardiology, cardiac computed tomography (CT), cardiovascular magnetic resonance (CMR), and invasive coronary angiography [14]. Table 1 summarizes these technologies' functions in CVDs. These imaging tools enable detailed patient phenotyping, enhancing the management of conditions like CAD and HF. They also help customize treatment plans and identify therapeutic targets [15].

An example is an article that doesn't go into depth about how precision medicine distinguishes between BrS and Brugada phenocopy (BrP). However, it gives some clues that can help us differentiate, reach a diagnosis, and plan for therapy. First, genetic testing shows mutations in SCN5A in BrS but not in BrP. Moreover, precision medicine implicates etiological factors by using advanced diagnostic tools such as metabolic panels, imaging studies, and detailed clinical histories to differentiate between BrS and BrP. After identifying the causes, precision medicine helps to set personalized treatment strategies. For example, correcting metabolic disturbances and electrolyte imbalances can reverse electrocardiogram (ECG) changes seen in BrP [16].

On the other hand, however, there is a notable trend nowadays that incorporates Noninvasive modalities such as CT, magnetic resonance imaging (MRI), and duplex ultrasonography. Such integration allows healthcare professionals to deliver more precise and efficient care to patients with CV issues. Table 2

**TABLE 1** | Advanced Medical Imaging Technologies main functionalities in cardiovascular diseases.

| Advanced Medical Imaging Technologies | Description |
|---|---|
| Echocardiography | Used for diagnosis and treatment of cardiac conditions |
| Nuclear cardiology | Provides detailed patient phenotyping |
| Cardiac computed tomography (CT) | Facilitates customization of treatment plans |
| Cardiovascular magnetic resonance (CMR) | Identifies precise therapeutic targets |
| Invasive coronary angiography | Enhances management of coronary artery disease (CAD) and heart failure |

*Source:* Created by Nour Yassin [1, 5] based on Achenbach et al. [14].

**TABLE 2** | Noninvasive modalities and their use in the cardiovascular field.

| Noninvasive modalities | Description |
|---|---|
| Computed tomography | Delivers precise and efficient care to patients with cardiovascular issues |
| Magnetic resonance imaging | Enhances diagnosis and treatment |
| Duplex ultrasonography | Provides Noninvasive imaging for cardiovascular conditions |

*Source:* Created by Nour Yassin [1, 5] based on Nahrendorf and Weissleder [17].

provides an overview of noninvasive modalities and their use in the CV field. Additionally, emerging technologies like artificial intelligence (AI), machine learning (ML), and molecular imaging techniques are playing prominent roles in advancing CV treatment modalities and options. By combining both modalities: the innovative technologies and the traditional imaging methods, healthcare providers can take benefit and work to improve the interventions that target CVDs [17] (Table 2).

## 3 | Advanced Imaging Tools for Precision CV Medicine

The trend in CV imaging methods has evolved significantly and this is driven by advancements in technology and the quest for higher resolution, greater accuracy, and enhanced diagnostic and therapeutic capabilities [18].

### 3.1 | Chest X-Rays and Ecocardiography

For decades, traditional imaging methods like Chest X-rays and standard echocardiography have played a significant role in detecting certain CVDs such as HF and valvular diseases. These techniques remain crucial in the initial assessment of cardiac structure and function due to their affordability and ease of execution [19].

These methods primarily utilize anatomical visuals but lack precision in evaluating characteristics of myocardial tissue and blood flow dynamics [20].

### 3.2 | Cardiac CT Scan (CCTS), Cardiac Positron Emission Tomography (PET) Scan and Coronary CT Angiography (CCTA)

Due to the limitations of traditional cardiac imaging techniques, some modern noninvasive technologies have become crucial to address these challenges. These include a CCTS and a Cardiac PET Scan.

CCTS uses ionizing radiation to create detailed cross-sectional images of the heart, which are crucial in diagnosing CAD, by utilizing coronary artery calcification quantity to create a score known as coronary artery calcium scoring. Though useful, its predictive value is somewhat constrained, as an elevated score is influenced by multiple factors and, therefore less specific [21]. CCTA has revolutionized the noninvasive evaluation of CAD by allowing for the visualization of the coronary lumen, stenosis, and plaque characteristics in three dimensions through various cardiac CT parameters, including calcium scoring. Due to the high specificity of this technique, it is the gold standard for evaluating specific arrays of symptoms related to CAD, especially in low and intermediate-risk patients [22].

Cardiac PET Scan relies on inherent tissue properties for image contrast, utilizing radiotracers like Rubidium-82 (Rb) and Nitrogen-13-ammonia (N-ammonia), which has advanced our understanding of integrative biology and enabling early disease detection and precise diagnosis [23]. The integration of PET/CT imaging, represents a significant advancement in myocardial perfusion imaging. This innovation has notably abbreviated imaging procedures and minimized radiation exposure, making it invaluable in patient care and precision treatment planning [24].

### 3.3 | Cardiac MRI

Cardiac MRI stands out as the most dependable method of cardiac imaging, thanks to its precision, reliability, and specificity. It serves various purposes, including risk assessment, noninvasive evaluation of ventricular volume and function, determination of myocardial viability, tissue analysis, assessment of chamber size and function, and detection of heart wall movement. Its versatility establishes it as the gold standard for investigating numerous cardiac conditions [25].

### 3.4 | Cardiac Imaging Enhancing Precision Medicine Through Modern Technologies and AI

Modern imaging methods as stated above have generally helped improve diagnostic accuracy and patient care, for instance, a comparative study between cardiac MRI and echocardiography established that MRI had a very high sensitivity (88%) and specificity (99%) in detecting ventricular thrombus as compared to echocardiography which had 24% sensitivity although this was shown to improve when the echocardiography was contrast mediated [26, 27]. However, the real value of advanced imaging techniques lies in how they help enable personalized data-driven decisions in patient management, as opposed to traditional imaging techniques [28].

A critical evaluation of these modern techniques established that despite the excellent anatomical visualization of cardiac CT, it is still limited, as it relies mainly on calcium scoring, which is influenced by a wide range of factors and does not assess the heart's function. In contrast, cardiac MRI is less harmful, as it does not utilize ionizing radiation and still provides comprehensive information about the heart's function and structure, making it preferable to those who require multiple

imaging or for which ionizing radiation is contraindicated, unlike cardiac CT where the patients can get exposed to as much as 10–20 mSv of radiation, therefore posing a long term risk [29]. The cost evaluation of these modern imaging methods differs in different regions. A review of the application of the European CV Magnetic Resonance registry data to the German, United Kingdom, Swiss, and United States health care systems shows that cardiac MRI costs more than cardiac CT in these regions, however, the cost-effectiveness of the imaging use depends largely on the patient's case [30]. The choice between these modalities often depends on the patient's specific needs, as these modalities complement each other in clinical practice, as they can be used in different clinical scenarios, emphasizing the importance of precision medicine.

The future of CV imaging in precision medicine lies in the seamless integration of imaging data with other omics data has notably enhanced patient management. This merging of insights from genomics, proteomics, epigenomics, transcriptomics, and metabolomics with imaging results offers a comprehensive grasp of disease mechanisms, enabling tailored treatment approaches. By amalgamating diverse data streams, clinicians acquire insights into both molecular underpinnings and anatomical-functional aspects of pathologies, thus advancing precision medicine and patient care [28, 31]. However, AI-driven predictive models are expected to play a crucial role in this process, as they help in correlating the outcome with genetic and molecular information and also interpreting complex imaging data. This will help optimize personalized care and improve treatment outcomes, as opposed to population-based strategies [32].

In recent times, the use of AI, ML, and deep learning (DL) have significantly improved various fields in medicine, by improving the accuracy, efficacy, and scope of several technologies. Concerning CV imaging, AI such as deep neural networks (DNNs), convolutional neural networks (CNNs), and Super-Resolution DL Reconstruction (SR-DLR), which uses complex algorithms to improve the imaging qualities and interpretation of ECG, transthoracic echocardiography, Cardiac CT, and MRI images, have shown to improve the diagnostic quality of these imaging techniques, make concrete inferences using several variables and the high-resolution images, therefore, facilitating adequate management [33]. A comprehensive study by Ribeiro et al. in 2020 developed a DNN model that outperformed cardiologist residents in identifying abnormalities in ECG. Several studies have also established the impact of AI and ML, as they have been used to classify and segment CV lesions, predict mortality and morbidity, compare different variables and metrics, and help in treatment planning [34]. These models essentially help to improve clinical standards [35]. As we forge forward, in as much as AI and ML can enhance the quality of care, we should be cautious, as these were models created by health professionals using data from previous images and investigations and, therefore are liable to biases and this is a major downside to AI models, as sometimes, the operations of this model are opaque to health professionals, this is called “the black box” [36, 37]. For AI and ML to be fully implemented, more studies need to be done on the impact of AI and ML to validate these models, and standardized protocols of interpretation need to be in place to improve reproducibility. Also, explainable AI, an emerging field of AI can help to mitigate the black box concern, as it aims to make AI algorithms transparent and easily interpretable, therefore making clinicians benefit from not only the predictive power of AI but also the logic behind the models' outputs, which is crucial in the medical field [38].

In regard to precision medicine, AI, ML, and DL produce comprehensive interpretations of CV images, and with the advancement of technology, they are expected to produce more holistic results, therefore improving the quality of management of patient-specific care [39, 40]. A systematic review by Abbaoui et al. highlighted the importance of AI in precision medicine and concluded that it is a dynamic revolution toward achieving precision medicine due to the endless scope of AI [41].

## 4 | Precision Medicine in CV Imaging: Diagnosis and Risk Stratification

### 4.1 | The Role of Multimodality Imaging in Precision Medicine

With the development of technology in contrast agents, software, hardware, and tailored tracers, multimodality CV imaging's significance in precision medicine is growing as it becomes more advanced. Compared to a clinical examination, imaging can diagnose patients at an earlier stage of the disease, determine a patient's evaluation more precisely, provide a more detailed description of the problem, and help forecast each patient's assessment [14].

### 4.2 | Arrhythmias and Risk Assessment

When diagnosing and evaluating arrhythmias, precision medicine is fundamental. Precision medicine allows for accurate identification of arrhythmias and individual risk factor assessment by combining cardiac electrophysiology studies with modern imaging modalities like cardiac MRI, CT angiography, and echocardiography [42]. Predictive capacities can discover structural traits linked to an increased risk of arrhythmias and complications. This enables preemptive care to avoid unfavorable outcomes such as stroke or HF. This approach helps clinicians create individualized treatment plans based on a patient's unique cardiac anatomy and function [43].

### 4.3 | Acute Coronary Syndromes (ACS) and High-Risk Plaques (HRP)

There is also potential to recognize patients at specific risk for ACS by using imaging to define HRP and ascertain the best course of treatment, such as medication versus invasive procedures [14].

### 4.4 | Imaging Techniques for CVDs

High-resolution imaging of the heart's tissue is made possible by cardiac MRI, which is crucial for detecting diseases including cardiomyopathy and myocarditis. It also allows for a thorough

evaluation of the heart's viability, perfusion, and scar tissue during myocardial infarction. With a high sensitivity for ruling out CAD, CT angiography (CTA) produces three-dimensional pictures of the coronary arteries that enable precise visualization of stenosis and plaques. However, CTA is associated with ionizing radiation and could lead to contrast-induced nephropathy in susceptible patients [44]. Echocardiography is an ultrasound-based modality that provides real-time imaging for assessing heart function, valve disease, and hemodynamics. This helps identify regional wall motion anomalies symptomatic of CAD.

Precision testing is a revolutionary tool for identifying patients with nonobstructive CAD who are at risk for CV events [14, 45].

CCTA was found to be superior to functional testing in the major PROMISE study (Prospective Multicenter Imaging Study for Evaluation of Chest Pain, $n = 10{,}003$) for the identification of patients with nonobstructive CAD who were at risk for CV events. There was a substantial rise in the likelihood of events associated with slightly abnormal (hazard ratios [HR] 2.94; 95% confidence interval [CI] 1.64–5.26), moderately abnormal (CCTA/7.67; 95% CI3.83–15.37), or severely abnormal (CCTA/10.13; 95% CI5.15–19.92) CCTA (all $p < 0.001$) in comparison to the results of the normal CCTA test [14]. Based on the results of the CCT scan, the introduction of preventative treatment was linked to a 34% relative risk reduction in all-cause mortality and myocardial infarction (MI) at 12 months (HR0.66; 95% CI 0.44–1.00; $p = 0.049$) [46]. In patients with stable chest pain, adding CCTA to standard therapy resulted in a substantially decreased 5-year risk of CV mortality from MI compared to standard care alone, according to the results of the randomized, open-label Scottish CT of the HEART Trial (SCOT-HEART) study [45].

### 4.5 | Recommendations and Perspectives

Current European Society of Cardiology (ESC) recommendations for the diagnosis and management of chronic coronary syndromes propose coronary CCTA and imaging-based stress testing as noninvasive diagnostic techniques based on a vast body of evidence. Thus, patients with a low to medium risk of CAD are advised to undergo CCTA [47]. By combining several diagnostic modalities imaging methods in precision medicine collectively contributes to the individualization of the therapy [48].

## 5 | Precision Medicine in Advanced CV Imaging: Treatment Planning and Monitoring

Precision medicine aids in the development of focused treatment plans by using imaging to pinpoint the precise type and location of arrhythmias. Imaging, for example, can identify the source of aberrant electrical activity and guide therapies such as catheter ablation or pacemaker or defibrillator implantation [49]. Treatment-related changes in the structure and function of the heart can be monitored with serial imaging evaluations. This continuous assessment is essential for monitoring treatment response and enhancing therapy. Integrating imaging results with genomic data is another comprehensive strategy that helps identify genetic predispositions to arrhythmias and tailor therapies accordingly. One such strategy is pharmacogenomics, which optimizes drug selection and dosage [50, 51].

When determining whether coronary atherosclerotic lesions will respond to medication therapy vs those that offer a serious danger and necessitate invasive therapies, imaging plays a key role [52]. Apart from luminal stenosis, lesion physiology plays a crucial role in ascertaining the need advantages over revascularization. Clinical Results Using Aggressive Drug Evaluation and Revascularization (COURAGE) Trial showed that, as compared to optimum medical treatment (OMT), revascularization based on anatomical stenosis alone did not improve the risk of mortality from MI [53]. Measurement of fractional flow reserve (FFR) might yield a more precise depiction of disease activity. Revascularization can be safely postponed in patients with an FFR > 0.8, as demonstrated in the FAME trials [54, 55], in contrast to angiography-guided treatment (FAME22) or OMT (FAME223).

However, in the FAME2 study, compared to those treated interventionally, around 50% of patients with FFR-positive lesions treated with OMT remained event-free and saw no change in angina rate [55, 56].

As with FFR negative lesions, hypophosphatasia (HPP) negative lesions have a significant negative predictive value. Thus, the next course of action could be to identify a subset of patients who have FFR-positive but HPP-negative lesions and who potentially benefit from OMT rather than revascularization. Some have argued that towering walls may help identify these patients even more [56].

The utilization of AI in data processing, along with other technological breakthroughs, has the potential to strengthen the role of imaging in precision medicine by enabling more precise guiding of therapies and more insightful and accurate diagnostic evaluation. During coronary angiography, FFR has historically been measured invasively with the installation of a pressure wire. Currently, computational fluid dynamics an accurate, noninvasive way to assess FFR is using CCTA [57]. Comparably, routine angiography alone may be utilized to mimic FFR with good concordance to invasively pressure wire-derived FFR using computer software [58]. Future invasive coronary angiography procedures could benefit from the use of these technologies. Additionally, new software tools like “dynamic road mapping” might provide real-time, dynamic overlays of coronary contours from noninvasive imaging on live fluoroscopy. This might perhaps even permit the positioning of intracoronary devices without the need for further contrast injection, and it might aid in the guidance of percutaneous coronary procedures (PCI) [59]. Nuclear cardiology, which uses radioactive tracers to give personalized insights into heart health, is emerging as a crucial component of precision medicine [60]. Evaluation of myocardial perfusion and viability, assists in the diagnosis of conditions such as HF and CAD. This facilitates the implementation of specific therapy, such as drug modifications or interventional procedures. It assesses preprocedure risks, aids in the creation of personalized treatment regimens based on thorough cardiac imaging, and maximizes the effectiveness of prescribed medications. Nuclear cardiology

monitors the course of the disease, assesses the effectiveness of medication, and finds problems early on to make sure treatment modifications are made on time [61]. Nuclear cardiology provides a holistic picture of cardiac health by combining it with other imaging modalities and using cutting-edge imaging techniques like PET and single photon emission CT. This improves therapy efficacy and diagnostic accuracy. Thus combining particular patient characteristics with comprehensive imaging data, precision medicine in advanced CV imaging aids in treatment and planning to provide patient-centered care [62].

## 6 | Challenges and Considerations in Implementing Precision Medicine in CV Imaging

Despite the importance of advanced imaging in CVD, there are numerous challenges to its acquisition, implementation, interpretation, and ethics.

Advanced imaging technologies face significant challenges related to acquisition, maintenance, and evaluation. Limited resources, including high acquisition expenses, inadequate infrastructure, unreliable power sources, and required expertise, pose significant obstacles, particularly in Low and Middle-Income countries (LMICs) [63]. Modern imaging methods often contain extensive encrypted data, necessitating sophisticated software for archiving, visualizing, and analyzing images. A deficiency in the operator's comprehension of software analytics presents an obstacle to generating artifact-free, high-resolution images and accurately interpreting them [64, 65]. Additionally, incorporating data from various imaging techniques like cardiac MRI, CT angiography, and nuclear imaging poses technical hurdles in data fusion and interpretation [64–66]. Enhancing the healthcare budget of LMICs, providing specialized training for operators, and establishing standardized protocols are essential steps to boost the procurement of advanced imaging devices and enable consistent and accurate multimodal imaging acquisition and analysis.

Uniformization and interpretation of imaging data across different healthcare settings present challenges. Variability among operators in executing and interpreting imaging techniques impacts consistent and reproducible image analysis, affecting data sharing, interprofessional/interhospital care, clinical decisions, and overall patient management [65]. Establishing standardized reporting protocols and implementing continuous education and training programs are crucial in reducing interobserver variability and ensuring reliable interpretation of imaging results.

Ethical and normative implications arise from using patient-specific image data. Utilizing patient information without proper protocols and consent raises concerns about patient privacy [67]. The use of patient-specific image data may unintentionally sustain biases and exacerbate healthcare disparities. These biases may emerge during data collection, processing, and analysis. Insufficient representation of certain demographic groups in datasets can result in inaccuracies or disparities in diagnosis and treatment suggestions. Addressing continuous monitoring, adhering to ethical protocols, and tackling discrimination in patient-specific image data utilization is essential for fairer and more inclusive healthcare practices, enhancing patient outcomes and reducing healthcare disparities [68].

Sophisticated devices and software are needed for precision medicine, which is a challenge in low-resource centers. However, ongoing efforts to reduce costs and improve accessibility in LMICs, including advancements in technology, collaboration with international organizations, political will, and training programs, show promise [69]. One will argue that these efforts are not feasible and how long will it take to achieve this in LMICs. Just like the case of electronic medical records (EMR), which seems like an unattainable feat in LMICs, it is now being used in a significant part of this region with incremental progress [70, 71]. Precision medicine will not be attainable in low-resource settings as fast as it is being implemented in high-income countries, however, if significant progress can be made on the efforts listed above, it is an achievable feat.

**TABLE 3** | Challenges and recommendations for precision cardiovascular imaging implementation.

| Key challenges | Sub-challenges | Recommendations |
|---|---|---|
| Technical challenges | • Limited availability of resources<br>• Lack of expertise and operator's technical know-how<br>• Poor data fusion and interpretation from multiple imaging techniques | • Increasing health budget<br>• Specialized training for operators<br>• Developing standardized protocols |
| Uniformization and interpretation of imaging data | • Inter-operator technique variability | • Establishing standardized reporting protocols<br>• Continuous education/training programs |
| Ethical and normative implications | • Lack of consent<br>• Data biases and discrimination | • Strict adherence to ethical guidelines<br>• Diversity and Inclusivity in Data Representation<br>• Continuous Monitoring and Evaluation |

*Source:* Created by Innocent Chijioke Dike [1, 3].

Table 3 summarizes the key challenges and recommendations regarding CV precision medicine.

## 7 | Solutions for Advancing Precision CV Imaging in Clinical Settings

Noninvasive CV imaging modalities such as echocardiography, nuclear cardiology, cardiac CT, and CMR play a critical role in precision medicine for CV illnesses [72]. Advances in CT imaging, particularly ultrahigh-resolution CT, have significantly improved vascular assessment accuracy. Precision cardiology can further improve by incorporating ML methods for disease characterization [73]. The use of 18F-labeled PET radiotracers in nuclear cardiology has the potential to revolutionize precision medicine by providing a comprehensive assessment of the heart's metabolic and functional condition [14].

Health professionals must collaborate to develop precision CV imaging in clinical settings [74]. Combining radiology and cardiology curricula and integrating AI and laboratory medicine are crucial. Many papers highlight the necessity of health professionals working together to advance CV care [75, 76].

Large infrastructural and technological investments are necessary for integrating sophisticated imaging into precision medicine [77]. Molecular imaging holds great promise. Addressing informatics needs, including data collection, interoperability, and education, is essential [78, 79].

Various educational and training initiatives have been created to improve precision imaging processes. E-learning and interactive teaching systems in ultrasound and medical imaging can enhance student learning [80]. Virtual reality simulation can boost medical imaging students' technical proficiency, showcasing the potential to improve precision imaging technique training [81].

## 8 | Conclusion

Advanced noninvasive imaging modalities are crucial for precise phenotyping of individuals with heart disease, specifically CAD and HF. These techniques, including CV imaging, play a key role in detecting various conditions, evaluating coronary lesions, measuring myocardial damage, and determining HF aetiologies. Enhanced imaging contributes to personalized patient care, improving sensitivity, accuracy, and prognostic evaluations, ultimately influencing treatment decisions and outcomes in CAD and HF patients.

Together with translational genomic, transcriptomic, proteomic, and metabolomic techniques, advances in AI, ML, and computer algorithms will be crucial for improving our knowledge of diseases and creating novel, focused treatments.

The field of precision medicine in CV imaging is expanding rapidly due to advancements in technology. Research and clinical studies have shown that using customized data and precise imaging can significantly improve patient outcomes. Through ongoing research and collaboration, personalized medicine is becoming achievable rather than a utopian dream.

### Author Contributions

**Poliana Zanotto Manoel:** writing–original draft, methodology, formal analysis, data curation. **Innocent Chijioke Dike:** data curation, formal analysis, methodology, writing–original draft. **Heeba Anis:** data curation, formal analysis, methodology, writing–original draft. **Nour Yassin:** data curation, formal analysis, methodology, writing–original draft. **Magda Wojtara:** writing–review and editing, writing–original draft, formal analysis, data curation. **Olivier Uwishema:** data curation, supervision, formal analysis, project administration, methodology, writing–review and editing, writing–original draft, conceptualization. All co-authors approved the final manuscript. All co-authors have read and approved the submission. All authors have read and approved the final version of the manuscript.

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### Ethics Statement

The authors have nothing to report.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Olivier Uwishema had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

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