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Review Article

Cardiac magnetic resonance imaging in myocardial infarction with non-obstructed coronary arteries: diagnostic and prognostic value

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Abstract: Myocardial infarction with non-obstructed coronary arteries (MINOCA) occurs when patients experience a heart attack without significant coronary artery blockage despite showing acute coronary syndrome symptoms. Unlike stable atherosclerosis, MINOCA involves acute myocardial infarction (MI) without obstructive coronary artery disease (CAD). The diagnostic criteria included meeting the universal MI definition, non-obstructive coronary arteries on angiography (< 50% stenosis), and no apparent cause of the acute event. The causes include coronary, cardiac, and extracardiac origins, such as plaque rupture, coronary spasm, myocarditis, or pulmonary embolism. MINOCA affects 5-6% of patients with acute MI undergoing angiography, with variations based on demographic factors. Although MINOCA was initially believed to have a favorable outcome, recent findings have indicated that MINOCA patients have a worse prognosis than the general population. Current guidelines strongly advocate the use of cardiac magnetic resonance imaging (CMR) to evaluate suspected MINOCA cases. However, multiple studies have demonstrated that CMR may fail to detect some instances of MINOCA, particularly in cases of mild inflammation or minor infractions. This could lead to a false-negative diagnosis requiring further testing. This review aimed to evaluate the diagnostic and prognostic value of CMR in patients with potential MINOCA.

Keywords: Myocardial infarction, non-obstructive coronary, myocardial infarction with non-obstructive coronary arteries, magnetic resonance imaging

Introduction

In patients presenting with acute coronary syndrome (ACS), prompt coronary angiography is crucial for identifying and addressing the underlying cause of coronary artery stenosis. However, despite experiencing acute myocardial infarction (MI), a subset of these patients surprisingly exhibits no evidence of obstructive coronary artery disease (CAD) upon angiographic examination. This condition is termed myocardial infarction with non-obstructed coronary arteries (MINOCA) [1, 2]. It is important to note that MINOCA is not merely about detecting atherosclerosis in stable individuals; it specifically refers to acute myocardial infarction without significant coronary artery blockage. Clinically and in terms of biomarker profiles, acute coronary events and MINOCA share striking similarities [3], making differentiation challenging without further investigation.

The established diagnostic criteria for MINOCA include fulfillment of the universal definition of

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MI, the presence of non-obstructive coronary arteries on angiography (defined as < 50% stenosis), and the absence of any clinically apparent specific cause for the acute presentation. The underlying causes of MINOCA are diverse and can be broadly categorized into coronary, cardiac, and extracardiac origins. Coronary causes encompass conditions such as occult plaque rupture or erosion, coronary artery spasm, spontaneous coronary artery dissection, coronary embolization, and coronary microvascular disorders. Cardiac causes include myocarditis, Takotsubo cardiomyopathy (TTC), cardiac trauma, and tachyarrhythmia. Extracardiac causes involve conditions like stroke, pulmonary embolism, sepsis, renal failure, and hypoxemia. Therefore, MINOCA should be regarded as an initial, working diagnosis that necessitates further investigation to determine the precise underlying cause [4, 5].

Epidemiological studies have shown that MINOCA is a common condition. Among all patients presenting with acute MI who undergo coronary angiography, 5-6% are diagnosed with MINOCA [6]. Large-scale studies, such as the SWEDEHEART and VIRGO investigations, have reported prevalence rates of 8.0% and 11.1%, respectively [7, 8]. Furthermore, research in Japan has indicated a prevalence of 10.2% [9], highlighting the consistent presence of MINOCA across diverse populations. Interestingly, MINOCA exhibits distinct demographic patterns compared with MI with obstructive coronary artery disease (MICAD). Younger individuals and females were disproportionately affected by MINOCA. Specifically, studies have shown a higher prevalence in younger patients (58.8% vs. 61.3%, $P < 0.001$) and women (43% vs. 24%, $P < 0.001$) than in patients with MICAD [6]. Additionally, individuals with MINOCA are less likely to present with dyslipidemia and traditional CAD risk factors such as diabetes mellitus, hypertension, family history of MI, and tobacco addiction [10]. Notably, MINOCA appears to be more prevalent in non-white patient populations [7]. Electrocardiographically, both ST-elevation myocardial infarction (STEMI) and non-ST-elevation myocardial infarction (NSTEMI) patterns are observed in MINOCA, with NSTEMI being more frequent, accounting for over two-thirds of the cases [11]. Although STEMI is often associated with complete coronary artery occlusion, NSTEMI is less commonly associated with this condition. Understanding obstructive CAD as a primary driver of acute MI has historically shaped treatment strategies centered on revascularization via percutaneous coronary intervention (PCI) [12].

The clinical presentation of MINOCA closely mimics that of MICAD [4], posing a significant diagnostic dilemma for clinicians when coronary angiography reveals non-obstructed arteries. The lack of an immediate apparent cause for the myocardial infarction makes the diagnosis complex, which has profound implications for patient prognosis, treatment pathways, and long-term management [13]. The underlying etiology of MINOCA is diverse. A thorough evaluation to identify the precise cause is crucial in all MINOCA cases because treatment strategies are highly dependent on the underlying pathology [14]. Differentiating between ischemic and non-ischemic causes is particularly important for personalized therapeutic approaches for MINOCA patients, given their distinct clinical and demographic profiles compared with typical acute MI patients [15].

Initially, MINOCA was considered to have a relatively benign prognosis. However, accumulating evidence has challenged this view, demonstrating that patients with MINOCA actually face a less favorable prognosis compared to the general population. This realization, coupled with the growing recognition of MINOCA's prevalence, has spurred increased research efforts aimed at standardizing diagnostic approaches and optimizing treatment strategies. In this context, cardiac magnetic resonance imaging (CMR) has emerged as a pivotal diagnostic tool. Leading cardiac societies, including the American Heart Association (AHA) and the European Society of Cardiology (ESC), now strongly recommend CMR (Class 1B recommendation) in their guidelines for the evaluation of patients with suspected MINOCA [16]. CMR's diagnostic strength of CMR lies in its non-invasive nature, ability to consistently and accurately characterize myocardial tissue, and capacity to differentiate between various etiologies of myocardial injury.

In clinical practice, CMR imaging plays a crucial role in distinguishing between the different causes of myocardial injury that can present with overlapping clinical and laboratory find-

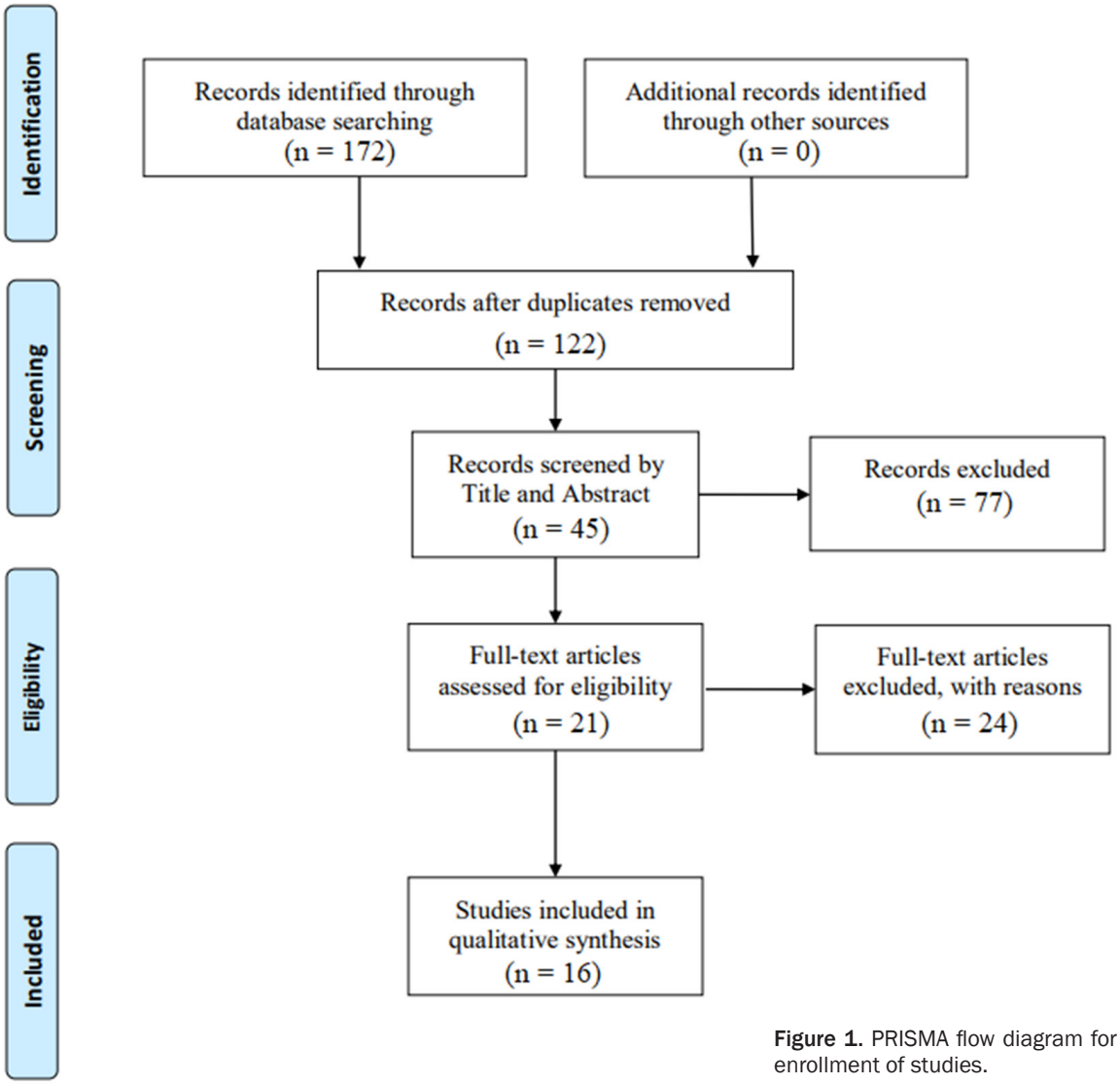

Figure 1. PRISMA flow diagram for enrollment of studies.

ings. Conditions such as acute MI, myocarditis, and TTC can mimic each other during their initial presentation. However, it is also important to acknowledge that CMR may not detect all cases of MINOCA, particularly when the infarction is small or when the inflammatory responses are minimal. This potential for false-negative results necessitates careful consideration and may warrant the use of complementary diagnostic modalities to confirm the diagnosis in certain cases [17, 18].

Therefore, this review is dedicated to comprehensively evaluating the diagnostic and prognostic value of CMR in patients suspected to have MINOCA. We aimed to explore both the advantages and limitations of CMR in the context of MINOCA detection. Furthermore, we discuss crucial considerations for the diagnosis of MINOCA, highlighting potential future directions in this evolving field.

Material and methods

Search strategy

We reviewed the relevant literature regarding the use of CMR imaging for the diagnosis of MINOCA. The study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (**Figure 1**). The research was conducted in PubMed, Scopus, Web of Science, and Google Scholar databases between

January 2020 and May 2024. It used Advanced Search Builder, and the keywords were searched in [Title OR Abstract]. We have filtered only research articles published in English language and using the terms '(Myocardial Infarction with Non-obstructed Coronary Arteries [Mesh]) AND (Cardiac magnetic resonance imaging [Mesh])'.

Inclusion and exclusion criteria

The systematic review included original publications evaluating the use of CMR imaging for the diagnosis of MINOCA and research evaluating the prognostic usefulness of CMR for MINOCA. The selection criteria were as follows: investigations focusing on patients with a working diagnosis of MINOCA, studies employing CMR assessment techniques, and research reporting both the number of patients diagnosed with specific conditions and the total number of participants evaluated. Studies were excluded if they involved participants aged < 18 years, individuals with end-stage renal disease, or cases in which the CMR protocol was not fully completed. Furthermore, this review excluded case reports and series with few patients, review articles without original data, editorials, letters, and conference papers. References within chosen research were examined for other pertinent literature.

CMR evaluation

The CMR protocol for MINOCA aims to characterize myocardial tissue and function to differentiate between ischemic and non-ischemic causes of injury and is typically performed within seven days of symptom onset, but no earlier than 24 hours. Standard cine imaging assesses global and regional left ventricular function, whereas T2-weighted imaging detects myocardial edema, a marker of acute injury. Late Gadolinium Enhancement (LGE) imaging is vital for identifying scars or fibrosis, with ischemic patterns (subendocardial/transmural) suggesting infarction and non-ischemic patterns (midwall, epicardial, patchy) indicating other cardiomyopathies such as myocarditis. Advanced optional techniques such as T1 mapping and extracellular volume quantification can further characterize tissues, and CMR angiography can be used to assess coronary abnormalities. Image interpretation by experienced readers focuses on LGE patterns, edema, and LV function to categorize MINOCA etiology, including myocardial infarction, myocarditis, and TTC. This comprehensive CMR protocol, emphasizing cine imaging, T2-weighted imaging, and LGE, enhanced the diagnostic accuracy of MINOCA, enabling tailored patient management by systematically evaluating myocardial function and tissue characteristics.

Data extraction and quality evaluation

Two authors (F.R. and A.M.) reviewed the titles and abstracts. After applying inclusion and exclusion criteria, study data were extracted in accordance with survey specifications.

Any applicable studies were added after a thorough search of the references in previously published review papers. In their complete form, 16 published research articles met our eligibility criteria. We included only the key conclusions relevant to our review for a few of them.

Discussion

Current diagnostic methods of MINOCA

MINOCA is a challenging diagnosis that requires a systematic approach to identify the underlying cause. Coronary angiography is the initial diagnostic test to rule out obstructive coronary artery disease (defined as ≥ 50% stenosis in a major epicardial vessel). However, angiography alone has limited ability to identify the underlying etiology of MINOCA, as it only provides information about the epicardial vessels [19]. Intracoronary imaging like intravascular ultrasound (IVUS) and optical coherence tomography (OCT) can identify subtle plaque disruption, dissection, or thrombosis that may be missed on angiography alone. These advanced imaging modalities can help uncover the underlying etiology in some MINOCA cases [20]. Another technique for diagnosis of MINOCA is invasive functional testing. Measurements of coronary flow reserve and index of microvascular resistance can assess the presence of coronary microvascular dysfunction, which is a common cause of MINOCA. However, these tests are not widely available and may not be performed routinely [21]. Also, CMR can provide valuable insights into the underlying pathology of MINOCA by assessing myocardial tissue characteristics. It can help differentiate between

ischemic and non-ischemic causes, such as myocarditis, TTC, and cardiomyopathies [22].

However, current diagnostic methods for MINOCA diagnosis have some limitations [23, 24]. First, MINOCA encompasses a wide range of underlying etiologies, making a single diagnostic approach challenging. Second, advanced imaging techniques such as CMR, IVUS, and OCT may not be readily available or interpreted by healthcare providers. Third, there is no universally accepted diagnostic algorithm for MINOCA, which leads to variability in clinical practice. The last limitation of the current methods is that much of the current understanding of MINOCA is based on extrapolating data from studies of myocardial infarction with obstructive coronary disease, which may not fully capture the unique characteristics of MINOCA [23, 24].

Diagnostic steps for MINOCA

The standard process for diagnosing MINOCA consists of three parts [25, 26]. First, the clinical setting needs to be carefully reevaluated to rule out non-cardiac causes of acute myocardial injury such as pulmonary embolus, infection, or chest trauma. As a working diagnosis, patients who have advanced to the second level are referred to MINOCA [27]. The second step should start with a thorough assessment of coronary angiography to rule out MICAD cases with missed high-grade narrowing and reevaluate peripheral occlusive lesions because coronary angiography frequently underestimates the severity of CAD. Additionally, patients with non-ischemic myocardial injuries must be excluded at this stage, which means that those with acute myocarditis or TTC diagnoses are no longer considered to have MINOCA. According to recent investigations, in the majority of MINOCA patients with no apparent cause, CMR was able to differentiate between MI and non-ischemic diseases [28, 29]. LGE and T2-weighted sequences are beneficial. Surface myocardial edema, a sign of acute myocardial damage, may be seen on T2-weighted imaging. Sub-endocardial or transmural LGE patterns denote an ischemic origin, whereas sub-epicardial or intramyocardial LGE patterns show non-ischemic originated myocardial damage. Consequently, myocardial edema based on T2-weighted imaging or ischemic-pattern LGE consistent with a coronary region is the definition of MI [30, 31]. In a study of 719 patients with ACS and non-obstructive coronary arteries, the final CMR diagnosis was acute MI in 26%, myocarditis in 26%, TTC in 12%, and other cardiomyopathies in 10%. Importantly, the final CMR diagnosis was associated with the long-term prognosis of patients with a working diagnosis of MINOCA [32]. The most recent Japanese guideline categorizes doing CMR on all patients presenting with a suspected MINOCA as Class IIa. However, it is now a Class I recommendation in US and European guidelines [33, 34]. The “true MINOCA” cases with ischemia-derived myocardial injury are isolated when MICAD, myocarditis, TTC, and other non-ischemic cardiomyopathies are ruled out. When identifying “true MINOCA” cases, the third and final stage seeks to identify the underlying ischemia process using intracoronary imaging or functional testing. Developing a suitable treatment plan for every MINOCA instance would be made possible by clarifying the specific ischemia process [35].

Although CMR is a valuable tool for assessing the myocardium in MINOCA patients, other coronary artery diagnostic tests, including IVUS and OCT, could be required to identify the underlying etiology of the disorders, which could include atherosclerotic plaque rupture, erosion, and spontaneous coronary dissection [25]. Additionally, provocative testing may support coronary vasospasm as a potential MINOCA etiology [36].

CMR imaging protocol

To avoid false-negative results or underestimation of disease severity in patients with MINOCA, CMR examination should be performed within seven days of symptom onset. It should also be noted that to avoid overt or early signs of pathology, examination should be performed at least 24 h after the onset of the disease [37]. Furthermore, if the CMR is negative but there is a clinical presentation of myocardial involvement, it may be necessary to repeat the test 1-2 weeks after the primary study to confirm the diagnosis. A targeted CMR imaging regimen customized for the evaluation of MINOCA should take no more than 30 to 40 minutes to complete and is achievable in most

Table 1. Specific techniques that CMR use to diagnose MINOCA

Quantitative Stress Perfusion Mapping	T1 and T2 Tissue Mapping
This technique measures myocardial blood flow (MBF) and perfusion reserve (MPR) to identify coronary microvascular dysfunction, which is a significant contributor to MINOCA.	These techniques help evaluate the presence of myocardial edema and damage, which can be indicative of various pathophysiological mechanisms in MINOCA patients.
Late Gadolinium Enhancement (LGE) Imaging	Epicardial Coronary Vasospasm Evaluation
LGE is used to assess the extent and functional impact of acute myocardial injury, which is crucial for diagnosing MINOCA and distinguishing it from other conditions.	CMR can help diagnose vasospasm by assessing the coronary arteries and identifying any abnormalities.
Advanced Tissue Characterization Techniques	Myocardial Function Assessment
Techniques like T1 mapping, LGE imaging, and high resolution (HR) LGE provide detailed information about the myocardium, which is essential for diagnosing MINOCA and guiding treatment.	CMR evaluates ventricular volumes, ejection fraction, and wall motion abnormalities to provide comprehensive functional and structural assessment of the heart.

patients, except for the most seriously ill [38-42].

A CMR study procedure for MINOCA patients includes cine imaging of cardiac structure and function of the left ventricle (LV), T2-weighted imaging for the presence of myocardial edema, and LGE imaging for the presence of myocardial injury. Furthermore, because of their high specificity, sensitivity, and diagnostic accuracy in detecting myocardial injury, new semiquantitative tissue characterization techniques, T1 and extracellular volume (ECV), and T2 mapping are recommended (**Table 1**). Myocardial perfusion assessment using pharmacological stress (e.g., adenosine) to determine reversible perfusion deficits is rarely necessary in patients with MINOCA, except for specific indications such as determining the extent of ischemia, and may be contraindicated in patients with acute MI. As a result, this assessment is not advised as part of the usual evaluation [39, 43].

Three probable etiologies explain the clinical appearance in up to 95% of patients of acute chest pain, unobstructed coronary arteries, and elevated troponin. These include acute myocarditis, acute MI, and cardiomyopathy, especially TTC. All of these disorders are easily diagnosed using a tailored CMR examination [44].

Studies conducted on using CMR for the diagnosis of MINOCA

MINOCA presents a significant diagnostic challenge in the cardiology field. Defined by the clinical presentation of acute coronary syndrome with elevated troponin levels, but without significant obstructive coronary artery disease on angiography, MINOCA encompasses a heterogeneous group of underlying etiologies. CMR imaging has emerged as a crucial tool for elucidating the underlying causes and risk stratification in patients with MINOCA. This discussion will sequentially review key studies that have investigated the diagnostic and prognostic utility of CMR in patients with MINOCA, highlighting the evolution of the evidence and the impact of CMR on clinical management.

Early investigations on the application of CMR in MINOCA focused on its diagnostic yield. A study by Luis et al. [45] in 2020 encompassing 227 patients with a working diagnosis of MINOCA demonstrated the substantial diagnostic capability of CMR. CMR identified non-structural cardiomyopathies in 43% of patients (n = 97), MI in 24% (n = 55), structural cardiomyopathies in 12% (n = 27), and pulmonary embolism in one patient. Similarly, Reynolds et al. [28] in 2021 reported that CMR revealed abnormal findings in 74.1% of 116 patients with suspected MINOCA. Among these abnormalities, ischemic patterns (MI or myocardial edema in a coronary distribution) were observed in 53.4% and non-ischemic patterns in 20.7%. Notably, they also underscored the incremental diagnostic value of multimodality imaging, demonstrating that it identified a cause of MINOCA in 84.5% of women, significantly surpassing the diagnostic yield of OCT alone ($P < 0.001$) or CMR alone ($P = 0.001$).

Building on these findings, Emrich et al. [46] examined 145 individuals with suspected MINOCA to determine the predictive value of early CMR. Within a median of three days post-cardiac catheterization, CMR identified a range of cardiac conditions in 98.6% of the cases (143 patients), including cardiomyopathies (33.1%), myocarditis (27.6%), true MI (15.1%), hypertensive heart disease (13.1%), and TTC (9.7%). Vago et al. [47] further corroborated the high diagnostic yield of early CMR (within 7 days of presentation) in suspected MINOCA patients. Their study found that CMR provided a diagnosis in 86% of patients, identifying conditions such as myocarditis, MI, TTC, and myocardial contusion.

Advancements in CMR techniques further enhance diagnostic accuracy. Lintingre et al. [43] evaluated the diagnostic value of high-resolution late gadolinium enhancement (HR-LGE) imaging in MINOCA patients. In a cohort of 229 patients, HR-LGE imaging refined the diagnoses in cases where conventional CMR was inconclusive. Specifically, in a subgroup in which conventional CMR findings were unclear, the incorporation of HR-LGE imaging led to diagnostic modification in 26% fewer patients and reduced the proportion of cases with unclear final diagnoses by 29%. This was particularly beneficial when standard CMR, ventriculography, and echocardiography were non-diagnostic, with a 48% rate of modified diagnoses in this subgroup.

The introduction of advanced CMR techniques such as T1 mapping and ECV mapping has further improved diagnostic capabilities. The SMINC-2 study [48], a follow-up of the SMINC-1 study [49], demonstrated that incorporating T1 mapping and ECV in CMR significantly increased the diagnostic rate in MINOCA patients from 47% in SMINC-1 (using conventional CMR) to 77% in SMINC-2 ($P < 0.001$). SMINC-2 also reported higher detection rates for myocarditis (17% vs. 7%; $P = 0.01$) and TTC (35% vs. 19%; $P = 0.002$) than SMINC-1, while the rates of MI and other cardiomyopathies remained similar.

Beyond diagnosis, CMR plays a critical role in risk stratification and influences the clinical management of MINOCA. In 2023, Bucciarelli et al. [50] assessed 135 MINOCA patients undergoing CMR with LGE approximately 28 days post-event. They found that CMR findings led to a change in treatment plans in 22% of the patients. Notably, one-third of the patients with ischemic MINOCA were initially misdiagnosed with myocarditis, highlighting the importance of CMR in differentiating between these conditions. Furthermore, their study indicated that patients with ischemic MINOCA had a higher rate of cardiac-related rehospitalizations (42%, $P < 0.001$) than those with non-ischemic MINOCA, although cardiac-related mortality was not statistically significantly different between the groups ($P = 0.36$).

In 2023, Konst et al. [51] also evaluated the prognostic value of CMR in 252 patients with MINOCA. CMR identified acute MI in 25%, myocarditis in 13%, non-ischemic cardiomyopathy (NICM) in 44%, and normal CMR in 15%. Importantly, CMR diagnosis strongly predicted patient prognosis even after adjusting for standard clinical variables. Patients with CMR diagnoses of acute MI, myocarditis, and NICM had significantly worse outcomes (increased rates of major adverse cardiac events [MACE]) compared to those with normal CMR. In 2020, de Barros et al. [52] further supported the prognostic value of CMR in 179 MINOCA patients. Over a 45-month follow-up period, they observed a MACE rate of 17.9% and a mortality rate of 3.8%. Patients with normal CMR findings had a significantly better prognosis (hazard ratio, 0.09; 95% confidence interval: 0.01-0.88; $P = 0.04$), indicating normal CMR as an independent predictor of favorable outcomes.

Ananthakrishna et al. [32] provided insights into long-term clinical outcomes in a cohort of 229 MINOCA patients who underwent CMR. With a median follow-up of 7.1 years, 24% of patients experienced MACE. Their findings demonstrated a significant association between CMR diagnosis and MACE ($P < 0.001$), with CMR diagnosis of acute MI and age identified as significant predictors of MACE. Emrich et al. [46] also reported prognostic variations based on CMR-defined etiologies, with myocarditis and TTC associated with better prognoses compared to structural cardiomyopathies. Vago et al. [47] similarly found a significant correlation between CMR diagnosis and 4-year mortality ($P < 0.0001$), with varying death rates across CMR diagnostic categories.

Tayal et al. [53] investigated the characteristics of MINOCA patients with and without CMR

abnormalities in a study of 34 patients. They found that while ECG and echocardiographic features were similar between the groups, Troponin T levels were significantly higher in patients with CMR abnormalities. This suggests that ECG and echocardiography have limited sensitivity for identifying ischemic changes detectable by CMR, underscoring the necessity of CMR in these patients.

Recognizing the limitations of standard CMR protocols, particularly in emergency settings, due to acquisition time and contrast agent requirements [54], Gatti et al. [55] in 2024 compared a short non-contrast CMR protocol to a standard comprehensive CMR in 179 MINOCA patients. Their findings revealed a strong correlation between the diagnoses made using short and standard CMR protocols. Expert readers achieved diagnostic agreement in 85% of the cases using the short protocol, whereas non-experts reached 73% agreement. This indicates that a short non-contrast CMR protocol could serve as a viable alternative to conventional protocols for specific MINOCA evaluations, potentially facilitating quicker diagnosis and broader application.

Cumulative evidence from these studies robustly supports the critical role of CMR imaging in the diagnostic evaluation and risk stratification of patients presenting with MINOCA. CMR not only provides a high diagnostic yield, identifying a diverse range of cardiac and noncardiac etiologies, but also offers significant prognostic information that informs clinical management and risk stratification. Advanced CMR techniques, including HR-LGE, T1 mapping, and ECV mapping, further enhance the diagnostic precision. While standard CMR protocols are valuable, emerging evidence suggests that shorter non-contrast protocols may offer a practical alternative in certain clinical scenarios, potentially increasing the accessibility and timely application of CMR in MINOCA. Despite the established utility of CMR, clinical concordance between CMR findings and initial clinical diagnoses remains an area for improvement [24], highlighting the ongoing need for education and integration of CMR into routine MINOCA diagnostic algorithms, as recommended by current guidelines [22]. Future research should continue to explore optimal CMR protocols, refine the diagnostic criteria, and further elucidate the long-term prognostic implications of CMR findings in the diverse spectrum of MINOCA.

Advantages and disadvantages of CMR from other diagnostic methods

CMR can provide a conclusive diagnosis in most cases involving MINOCA. According to previous research, CMR can detect the underlying cause in as many as 87% of patients with MINOCA, with the most prevalent diagnoses being acute MI, TTC, and myocarditis [48]. CMR can distinguish between ischemic and non-ischemic causes of MINOCA without invasiveness or radiation. This is more advantageous than invasive diagnostic procedures such as intravascular imaging and coronary angiography [56]. The capacity to identify these acute changes was optimized by conducting CMR within 1-2 weeks of presentation [17]. In addition, CMR offers a thorough evaluation of the heart's structural and functional characteristics, such as ventricular volume, ejection fraction, and wall motion abnormalities, which can prove the diagnosis and prognosis [40, 41]. CMR has been demonstrated to enhance outcomes and modify management in MINOCA patients compared with conventional diagnostic methods that do not incorporate CMR. Precise diagnosis of CMR can result in more personalized and targeted treatments [57].

However, CMR had some limitations. CMR cannot detect CAD or stenosis, as it is not intended to visualize the coronary arteries directly. Consequently, it is frequently necessary to administer supplementary tests, such as intravascular imaging or coronary angiography, to rule out obstructive coronary artery disease [58]. Also, the detection of all cases of MINOCA may not be possible with CMR, mainly if the infarction is minor or the patient has a low level of inflammation. This may result in false-negative diagnoses, necessitating additional testing to verify the diagnosis. Additionally, the accurate interpretation of CMR images necessitates specialized expertise, which may pose a constraint in environments where radiologists lack experience in MINOCA diagnosis [18, 55]. Another important thing is the timing of CMR. CMR is most effective when conducted early in MINOCA, as delayed imaging may result in the omission of certain features. Therefore, delays

Table 2. Advantages and disadvantages of CMR for diagnosis of MINOCA

Advantages	Disadvantages
• True diagnosis of Myocardial infarction (MI)	• Inability to identify coronary artery disease
• Distinguishing from non-Ischemic causes	• Potential false-negatives
• Evaluation of extent and functional impact of acute MI	• Interpretation complexity
• Non-invasive and radiation-free	• Cost and availability
• Early Detection	• Delayed imaging may miss some features
	• Limited diagnostic yield in certain cases

in getting access to CMR services can be a limitation [32, 46, 47, 59]. Additionally, access to CMR scanners is restricted, especially during hospital stays. Additionally, patients with non-conditional devices, those in the first trimester of pregnancy, or those with extensive kidney injury are relative contraindications for CMR imaging. In the literature, patients getting serial MRI scans have been reported to exhibit gadolinium accumulation in their brains [60]. Despite this possible disadvantage, it should be noted that the finding has unclear clinical importance because there has not been any evidence of a toxic effect to date, and it does not restrict the modality's use in clinical practice [61]. Ultimately, a cost-benefit analysis demonstrated that the utilization of CMR-guided therapy for patients diagnosed with MINOCA results in reduced medical care costs over the short and long term [62]. The advantages and limitations of CMR are summarized in **Table 2**.

Overall, although CMR has some limitations as an imaging tool for diagnosing MINOCA, various experts and the ESC Task Force strongly recommend it for evaluating patients with MINOCA, and its clinical utility has led to its inclusion in guidelines as a first-line diagnostic tool.

Conclusion and future directions

A comprehensive diagnosis of MINOCA includes a diverse array of non-coronary and coronary pathologies. To accomplish this, a combination of invasive and non-invasive imaging techniques is sometimes required, each with specific advantages and disadvantages as well as differing degrees of availability and experience in the local area. Therefore, to determine the cause of MI in the absence of obstructive coronary artery disease, a combination of multimodality imaging techniques, including CMR, IVUS, and OCT, is crucial. More research will be needed to ascertain whether the routine application of these techniques, particularly in MINOCA patients, improves clinical outcomes.

Disclosure of conflict of interest

None.

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