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REVIEW ARTICLE

Arrhythmic myocarditis and prevention of sudden cardiac death: current evidence, risk stratification, and management

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ABSTRACT

Myocarditis is an inflammatory myocardial disease with heterogeneous clinical manifestations ranging from chest pain to cardiogenic shock and malignant ventricular arrhythmias. Arrhythmic presentations represent an important clinical phenotype associated with an increased risk of sudden cardiac death (SCD). Contemporary studies suggest that ventricular arrhythmias occur in approximately 10% of hospitalized patients with acute myocarditis, frequently during the early inflammatory phase. Risk stratification requires integration of clinical presentation, ventricular function, arrhythmic burden, genetic variants, and findings on cardiac magnetic resonance imaging, such as late gadolinium enhancement. Management strategies include treatment of the underlying inflammatory process, guideline-directed heart failure therapy, anti-arrhythmic drugs, catheter ablation in selected cases, and implantable cardioverter-defibrillators for primary and secondary prevention. This review summarizes current evidence regarding epidemiology, mechanisms, risk stratification, and prevention of SCD in patients with arrhythmic myocarditis and highlights emerging concepts in imaging, genetics, and personalized management. (Hellenic Journal of Cardiology 2026;■:■-■) © 2026 Hellenic Society of Cardiology. Publishing services by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. INTRODUCTION

Myocarditis is an inflammatory disease of the myocardium with a highly variable clinical spectrum, ranging from asymptomatic myocardial injury to cardiogenic shock and sudden cardiac death (SCD).[1-3] Although many patients experience a benign clinical course, a substantial minority develop severe complications, including ventricular arrhythmias, heart failure, or fulminant myocarditis.[4-6]

Three principal clinical presentations of myocarditis are generally recognized:

1. Chest pain or infarct-like presentation
2. Heart failure presentation
3. Arrhythmic presentation

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CLINICAL PERSPECTIVE

Myocarditis is an inflammatory disease of the myocardium with a broad clinical spectrum ranging from mild chest pain to cardiogenic shock and sudden cardiac death (SCD). Among its clinical phenotypes, arrhythmic myocarditis has emerged as a particularly important presentation because of its association with malignant ventricular arrhythmias and adverse outcomes. Ventricular arrhythmias occur in approximately 10% of hospitalized patients with acute myocarditis, often during the early inflammatory phase. Although the absolute risk of SCD is lower than that in inherited cardiomyopathies, myocarditis remains a significant cause of arrhythmic death, particularly in younger individuals.

Ventricular arrhythmias in myocarditis typically occur in two phases, reflecting different mechanisms. During the acute inflammatory phase, myocardial edema, inflammatory cytokines, and conduction abnormalities promote electrical instability that may lead to polymorphic ventricular tachycardia or ventricular fibrillation. In the chronic or "healed" phase, myocardial fibrosis can create a substrate for scar-related re-entry circuits responsible for sustained monomorphic ventricular tachycardia.

Cardiac magnetic resonance imaging plays a central role in diagnosis and risk stratification. In particular, late gadolinium enhancement identifies myocardial injury and fibrosis and has been associated with an increased arrhythmic risk. Clinical assessment therefore integrates imaging findings with ventricular function and arrhythmic burden.

Management should be individualized according to the disease phase. Implantable cardioverter-defibrillators remain the cornerstone of secondary prevention, whereas wearable cardioverter-defibrillators may provide temporary protection during the early recovery phase.

Among these phenotypes, arrhythmic myocarditis has emerged as a clinically relevant entity characterized by ventricular tachyarrhythmias occurring either during the acute inflammatory phase or later as a consequence of myocardial scar formation.[7–9]

Understanding the mechanisms and predictors of ventricular arrhythmias in myocarditis is essential for risk stratification and prevention of SCD. Advances in cardiac imaging, particularly cardiac magnetic resonance (CMR), have improved the ability to detect myocardial inflammation and fibrosis and to identify patients at increased arrhythmic risk.[10–13]

This review summarizes current evidence regarding the epidemiology, mechanisms, clinical presentation, risk stratification, and management of arrhythmic myocarditis, with particular emphasis on strategies for prevention of SCD.

2. EPIDEMIOLOGY OF ARRHYTHMIAS IN MYOCARDITIS

Arrhythmias represent a frequent complication of myocarditis and may occur during both the acute inflammatory phase and the chronic phase characterized by myocardial fibrosis.

Recent clinical studies indicate that approximately **10% of hospitalized patients with acute myocarditis develop ventricular arrhythmias**, often within the first 24 h of admission.[14] In observational studies, cardiac arrhythmias overall were reported in nearly one-third of patients hospitalized with myocarditis.[15]

Myocarditis is also recognized as an important cause of SCD, particularly among young individuals and athletes. Autopsy-based studies suggest that myocarditis accounts for **approximately 6–10% of SCD in individuals younger than 50 years**.[16]

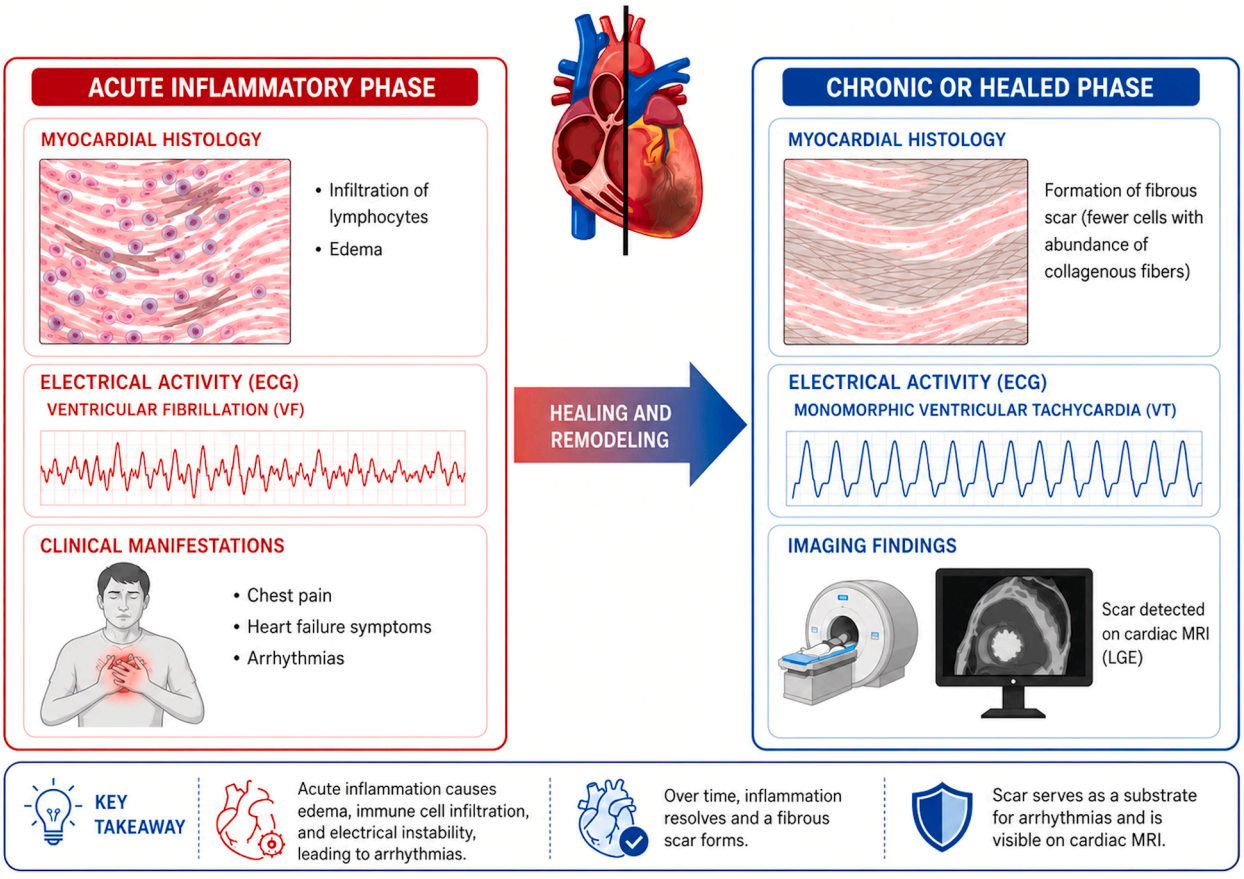
Although the absolute risk of SCD in myocarditis remains relatively low compared with that in inherited cardiomyopathies, the disease remains an important contributor to arrhythmic death in the younger population.

3. MECHANISMS OF VENTRICULAR ARRHYTHMIAS

The mechanisms underlying ventricular arrhythmias in myocarditis are dynamic and depend on the phase of disease. During the acute inflammatory phase, myocardial edema, cytokine release, myocyte injury, and disruption of intercellular coupling promote electrical instability. These changes may alter ion-channel function, calcium handling, and conduction velocity, favoring triggered activity, conduction block, and re-entry. In this setting, ventricular arrhythmias are often polymorphic and may include ventricular fibrillation, particularly in patients with extensive inflammation or hemodynamic compromise.[1,2,7,8]

As inflammation evolves, areas of heterogeneous injury and slow conduction may develop within the myocardium. This transitional phase can be characterized by both residual inflammatory activity and

FIGURE 1 **Biphasic pattern of ventricular arrhythmias in myocarditis**



Ventricular arrhythmias in myocarditis may arise from distinct but overlapping mechanisms according to disease phase. During the acute inflammatory phase, edema and active inflammation promote electrical instability and may lead to polymorphic ventricular tachycardia or ventricular fibrillation. During the chronic or healed phase, persistent myocardial fibrosis provides a substrate for scar-related re-entry and sustained monomorphic ventricular tachycardia

early reparative changes, creating an unstable substrate in which arrhythmias may reflect a combination of active inflammation and developing fibrosis.[7,8]

In the chronic or healed phase, persistent myocardial scar becomes the dominant arrhythmogenic substrate. Replacement fibrosis, detectable by late gadolinium enhancement on CMR, can create fixed regions of slow conduction that support scar-related re-entry and sustained monomorphic ventricular tachycardia. Thus, arrhythmic myocarditis can be conceptualized as a biphasic process (Fig. 1): early arrhythmias are mainly driven by active inflammation and edema, whereas late arrhythmias are more often related to residual fibrotic scar.[1,2,7,8]

4. CLINICAL SPECTRUM OF ARRHYTHMIC MYOCARDITIS

The arrhythmic manifestations of myocarditis are heterogeneous and include premature ventricular contractions, non-sustained ventricular tachycardia, sustained ventricular tachycardia, ventricular fibrillation, and sudden cardiac arrest. Life-threatening ventricular arrhythmias represent the most severe presentation and may occur even in patients with preserved left ventricular function.[1,2,9]

Long-term follow-up studies indicate that patients presenting with life-threatening ventricular arrhythmias have a substantial risk of recurrence during follow-up. This risk appears to be influenced by the

phase of disease, the persistence of myocardial scar or inflammation, left ventricular function, and arrhythmic burden. Therefore, clinical evaluation should not rely solely on ejection fraction but should integrate the arrhythmic phenotype with CMR findings and longitudinal reassessment.[10–17]

5. ROLE OF CARDIAC MAGNETIC RESONANCE

CMR has become the cornerstone non-invasive imaging modality for the diagnosis of myocarditis because of its ability to provide multiparametric tissue characterization. The original Lake Louise Criteria (LLC), introduced in 2009, relied on three qualitative imaging markers reflecting myocardial inflammation: myocardial edema, hyperemia/capillary leak, and necrosis or fibrosis detected by late gadolinium enhancement (LGE). More recently, the criteria were updated to incorporate quantitative parametric mapping techniques, which improve diagnostic accuracy and sensitivity for detecting myocardial inflammation. The updated LLC (2018) are based on the presence of at least one T2-based marker of myocardial edema and at least one T1-based marker of myocardial injury, reflecting the two major pathological processes in acute myocarditis: inflammatory edema and myocardial damage.[1,11]

Beyond diagnosis, CMR provides important prognostic information. The presence and extent of LGE have been associated with an increased risk of ventricular arrhythmias and adverse clinical outcomes.[10–12]

6. ENDOMYOCARDIAL BIOPSY IN ARRHYTHMIC MYOCARDITIS

Endomyocardial biopsy remains the reference standard for definitive etiological diagnosis of myocarditis, although it is not required in all patients.[1,2] In clinically stable patients with an infarct-like presentation, preserved ventricular function, and typical CMR findings, a non-invasive diagnostic approach is often sufficient. However, biopsy should be considered in patients with high-risk or atypical presentations in whom histological confirmation may influence management. These include patients with life-threatening ventricular arrhythmias, resuscitated cardiac arrest, recurrent or sustained ventricular tachycardia, high-grade atrioventricular block, cardiogenic shock, rapidly progressive or unexplained heart failure, recurrent myocarditis, or suspicion of specific forms such as giant cell myocarditis, eosinophilic myocarditis, immune checkpoint inhibitor-associated myocarditis, cardiac sarcoidosis, or virus-negative immune-mediated myocarditis.[1,2]

In arrhythmic myocarditis, biopsy may provide both diagnostic and prognostic information. Histology, immunohistochemistry, and viral genome analysis can distinguish lymphocytic myocarditis from giant cell, eosinophilic, granulomatous, or virus-associated forms, which differ substantially in prognosis and therapeutic implications. Identification of giant cell myocarditis, eosinophilic myocarditis, immune checkpoint inhibitor-associated myocarditis, or cardiac sarcoidosis is particularly relevant because these entities are associated with higher arrhythmic risk and may require prompt immunosuppressive or disease-specific therapy. Biopsy findings may also help interpret persistent ventricular arrhythmias or ventricular dysfunction when CMR findings are inconclusive or when there is concern for ongoing inflammation despite apparently healed disease.

Nevertheless, endomyocardial biopsy has important limitations. Diagnostic yield may be reduced by sampling error because myocardial inflammation can be patchy, and procedural risk, although low in experienced centers, is not negligible. Its clinical value depends on appropriate patient selection, integration with imaging findings, and expert histopathological, immunohistochemical, and molecular analysis. Therefore, biopsy should be viewed as a targeted diagnostic tool for selected high-risk patients rather than a routine test for all cases of suspected myocarditis.[1,2]

7. MANAGEMENT OF VENTRICULAR ARRHYTHMIAS

Management of arrhythmias in myocarditis depends on disease phase and clinical severity (**Tables 1** and **2**).

7.1. ACUTE PHASE. Treatment strategies include:

- management of the underlying inflammatory process
- anti-arrhythmic drugs
- intensive monitoring
- mechanical circulatory support when necessary

7.2. CHRONIC PHASE. Patients with persistent arrhythmic risk may require:

- anti-arrhythmic therapy
- catheter ablation
- implantable cardioverter-defibrillator

TABLE 1 Management strategies in arrhythmic myocarditis

Clinical scenario	Management
Acute myocarditis with ventricular arrhythmia	Intensive monitoring and anti-arrhythmic therapy
Hemodynamic instability	Mechanical circulatory support
Recurrent VT	Catheter ablation
Sustained VT/VF	ICD implantation
Recovery phase	Risk stratification and follow-up

8. DEVICE THERAPY: EARLY VERSUS DELAYED ICD IMPLANTATION AND THE ROLE OF WEARABLE CARDIOVERTER-DEFIBRILLATORS

Implantable cardioverter-defibrillators (ICDs) remain the cornerstone of secondary prevention of SCD in patients with sustained ventricular tachycardia, ventricular fibrillation, or resuscitated cardiac arrest not attributable to reversible causes. In myocarditis, however, the timing of ICD implantation is particularly challenging because arrhythmic risk is dynamic and may change after resolution of active myocardial inflammation.[1,2,18-23]

During the acute inflammatory or "hot" phase, malignant ventricular arrhythmias may be driven by edema, cytokine-mediated electrical instability, and transient conduction abnormalities.[7,8] In this setting, early ICD implantation may expose some patients to unnecessary long-term device-related complications if ventricular function and arrhythmic burden subsequently improve. For this reason, definitive ICD implantation is often deferred during the early phase when the arrhythmia is judged to be potentially reversible and when close monitoring and temporary protection are feasible.[1,24-28]

TABLE 2 Risk markers for ventricular arrhythmias in myocarditis

Category	Higher-risk features
Clinical presentation	Resuscitated cardiac arrest, sustained VT/VF, unexplained syncope, cardiogenic shock, recurrent myocarditis
Echocardiography	LVEF $< 50\%$, persistent LVEF $\leq 35\%$ after recovery phase, LV dilation, regional wall motion abnormalities, right ventricular dysfunction, biventricular involvement
CMR	Extensive LGE, septal or anteroseptal LGE, mid-wall LGE, ring-like or multifocal LGE, right ventricular LGE, persistent LGE on follow-up CMR, persistent edema or active inflammation
ECG/Holter monitoring	Non-sustained VT, frequent or complex ventricular ectopy, sustained monomorphic VT, recurrent ventricular arrhythmias after the acute phase
Electrophysiology	Inducible sustained monomorphic VT after resolution of acute inflammation
Genetics	Pathogenic variants associated with arrhythmogenic or dilated cardiomyopathy, especially desmosomal, FLNC, LMNA, or DSP variants
Biomarkers and disease activity	Persistent troponin elevation, persistent inflammatory activity, incomplete clinical recovery

Conversely, delaying ICD implantation may expose selected high-risk patients to recurrent life-threatening ventricular arrhythmias. Early ICD implantation may therefore be appropriate when arrhythmic events recur despite treatment, when sustained monomorphic ventricular tachycardia suggests a fixed scar-related re-entry substrate, when severe left ventricular dysfunction persists, or when additional high-risk features are present, including extensive or septal LGE, unexplained syncope, inducible sustained ventricular tachycardia, right ventricular involvement, or a pathogenic cardiomyopathy-associated genetic variant.[1,29-31] Thus, the decision should not be based solely on the occurrence of an arrhythmic event, but on the presumed mechanism, disease phase, reversibility of inflammation, ventricular function, CMR findings, and overall recurrence risk.

Wearable cardioverter-defibrillators may provide temporary protection during the recovery phase, particularly in patients with recent myocarditis, reduced left ventricular ejection fraction, extensive LGE, non-sustained ventricular tachycardia, or previous ventricular arrhythmias in whom immediate ICD implantation is not clearly indicated. This strategy allows time for anti-inflammatory treatment, optimization of heart failure therapy, recovery of ventricular function, and reassessment of arrhythmic risk after approximately 3-6 months.[1,24-27] At reassessment, ICD implantation may be reconsidered in patients with persistent left ventricular dysfunction, recurrent or inducible ventricular tachyarrhythmias, persistent extensive LGE, or evidence of an underlying genetic cardiomyopathy.[1]

However, wearable cardioverter-defibrillators also have important limitations. Their effectiveness depends on adherence and adequate daily wear time, and protection is absent when the device is removed. Inappropriate alarms or shocks, skin discomfort, sleep disturbance, anxiety, and impaired quality of life may reduce tolerance. Cost and access may also limit use in routine practice. In addition, available evidence in myocarditis is largely observational, and randomized myocarditis-specific data are lacking. Therefore, wearable cardioverter-defibrillators should be viewed as a bridge to recovery and risk reassessment rather

than a definitive substitute for ICD therapy in patients with persistent high-risk features.[1]

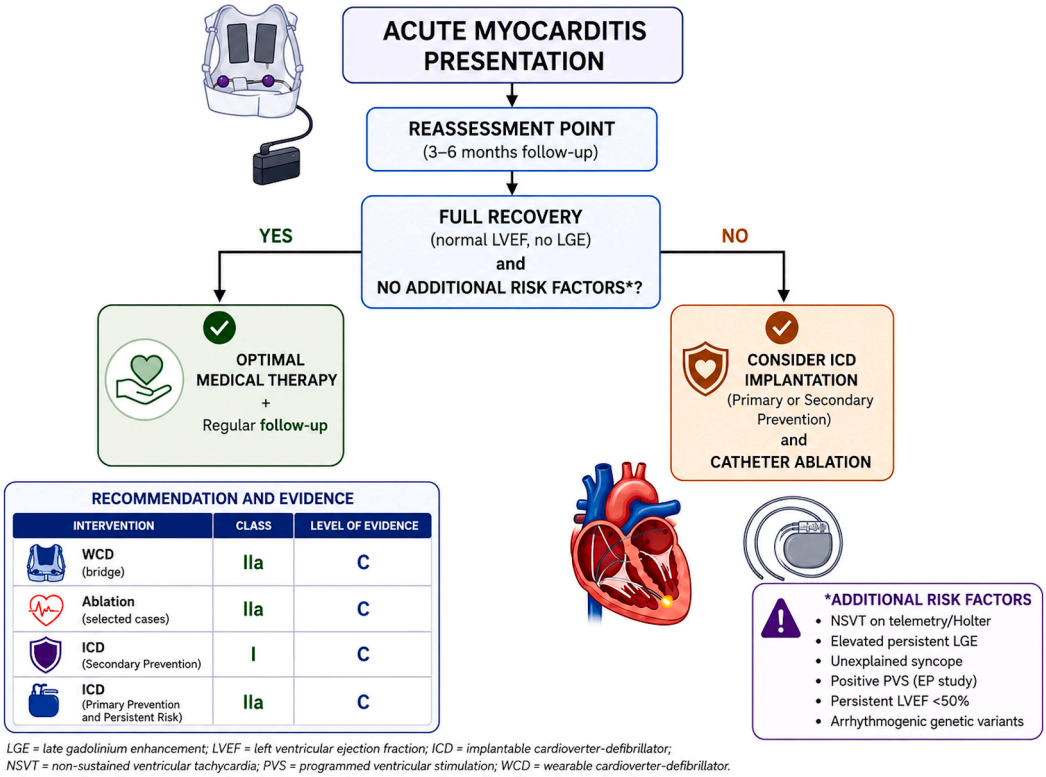
Overall, device therapy in arrhythmic myocarditis should be individualized. A delayed strategy with temporary protection is reasonable when arrhythmic risk is likely to be transient and recovery is expected, whereas earlier ICD implantation should be considered when the arrhythmogenic substrate appears established or when multiple high-risk markers persist despite resolution of active inflammation (Fig. 2).

9. GENETIC PREDISPOSITION, ARRHYTHMOGENIC CARDIOMYOPATHY OVERLAP, AND IMPLICATIONS FOR MANAGEMENT

Genetic predisposition is increasingly recognized as an important modifier of clinical presentation, arrhythmic risk, and long-term outcome in myocarditis.[29–31] Rather than representing a separate diagnostic domain, genetic assessment should be considered part of a multiparametric clinical workflow in selected patients with arrhythmic myocarditis. In this context, myocarditis may act as a trigger that unmasks an underlying inherited cardiomyopathy, or inflammatory myocardial injury may accelerate disease expression in genetically susceptible individuals.[1,31]

Genetic testing is not required in all patients with uncomplicated myocarditis. However, it should be considered when clinical features suggest a disproportionate arrhythmic phenotype or a possible inherited substrate. Patients most likely to benefit include those presenting with sustained ventricular tachycardia, ventricular fibrillation, resuscitated cardiac arrest, unexplained syncope, recurrent myocarditis, persistent left ventricular dysfunction after the acute phase, extensive or atypical non-ischemic LGE, right ventricular involvement, family history of cardiomyopathy or SCD, or electrocardiographic/imaging features suggestive of arrhythmogenic or dilated

FIGURE 2 **Risk-stratified management of ventricular arrhythmias in myocarditis according to the 2025 ESC Guidelines (see text for explanation)**



LGE = late gadolinium enhancement; LVEF = left ventricular ejection fraction; ICD = implantable cardioverter-defibrillator; NSVT = non-sustained ventricular tachycardia; PVS = programmed ventricular stimulation; WCD = wearable cardioverter-defibrillator.

Abbreviations: WCD = wearable cardioverter-defibrillator; ICD = implantable cardioverter-defibrillator; VT = ventricular tachycardia; NSVT = non-sustained ventricular tachycardia; LGE = late gadolinium enhancement; LVEF = left ventricular ejection fraction; PVS = programmed ventricular stimulation.

cardiomyopathy.[1] Genetic evaluation may also be appropriate when myocarditis occurs in association with frequent ventricular ectopy, recurrent non-sustained ventricular tachycardia, or a scar pattern that appears disproportionate to the severity of the inflammatory episode.

Several genes associated with inherited cardiomyopathies have been implicated in arrhythmic myocarditis. Desmosomal variants, particularly involving DSP and PKP2, may be associated with inflammatory myocardial episodes that clinically resemble myocarditis, often with subepicardial or ring-like LGE and a high arrhythmic burden.[1,29] Similarly, pathogenic variants in FLNC, LMNA, and TTN may predispose to ventricular arrhythmias, persistent ventricular dysfunction, and adverse remodeling after an inflammatory insult.[30] These observations support the concept that myocarditis and genetic cardiomyopathies may overlap, particularly with arrhythmogenic cardiomyopathy.[29-31] In some patients, the inflammatory presentation may be the first manifestation of a genetically determined cardiomyopathic process rather than an isolated post-viral or immune-mediated event.

This overlap has important implications for management. Identification of a pathogenic or likely pathogenic variant may justify closer follow-up, repeat CMR, extended rhythm monitoring, and a lower threshold for electrophysiological evaluation or ICD consideration, especially when combined with persistent LGE, ventricular dysfunction, syncope, or recurrent ventricular arrhythmias. Genetic findings may also influence exercise recommendations, as patients with arrhythmogenic cardiomyopathy-associated variants may require more stringent long-term restriction from high-intensity endurance exercise than patients with uncomplicated myocarditis. In addition, a positive genetic result should prompt referral for genetic counseling and cascade screening of relatives, because family members may carry the same variant and be at risk despite being asymptomatic.[1,28]

Conversely, the absence of a pathogenic variant does not exclude arrhythmic risk, and variants of uncertain significance should not be used in isolation to guide major therapeutic decisions. Genetic results must therefore be interpreted in the context of phenotype, family history, CMR pattern, ventricular function, and arrhythmic burden. The greatest clinical value of genetic testing is likely to emerge when integrated with imaging and electrophysiological markers to distinguish isolated myocarditis with transient risk from inflammatory presentation of an underlying cardiomyopathy with persistent long-term arrhythmic risk.[1]

10. RISK STRATIFICATION IN ARRHYTHMIC MYOCARDITIS

Risk stratification in myocarditis requires integration of clinical presentation, ventricular function, arrhythmic burden, CMR findings, and, in selected cases, electrophysiological and genetic data. No single marker is sufficient to accurately predict SCD risk, particularly because myocarditis is a dynamic disease in which inflammation, ventricular function, and arrhythmic substrate may change substantially over time.[1,7-9]

10.1. ECHOCARDIOGRAPHIC MARKERS. Echocardiography remains the first-line imaging modality for initial assessment and follow-up. The most widely used echocardiographic risk marker is reduced left ventricular ejection fraction. An LVEF below 50% should be regarded as abnormal in the context of myocarditis after a period of optimized medical therapy and resolution of active inflammation and identifies a higher-risk subgroup in whom ICD implantation may be considered.[1] Additional echocardiographic markers that may suggest increased risk include left ventricular dilation, regional wall motion abnormalities, right ventricular dysfunction, biventricular involvement, and persistent ventricular dysfunction during follow-up. Right ventricular involvement is particularly relevant because it may indicate a more diffuse inflammatory or cardiomyopathic process and has been associated with increased arrhythmic vulnerability in non-ischemic myocardial disease. Serial echocardiography is therefore useful not only to document recovery of systolic function, but also to identify patients with persistent remodeling who require further risk assessment.[1]

10.2. CMR MARKERS AND LGE PATTERNS. CMR provides complementary information by identifying myocardial edema, active inflammation, and replacement fibrosis.[10,12,13] The presence of LGE is one of the most important imaging markers of myocardial injury and has been associated with adverse outcomes and ventricular arrhythmias. However, the prognostic value of LGE depends not only on its presence, but also on its pattern, extent, location, and persistence. Extensive LGE, multifocal LGE, septal or anteroseptal involvement, mid-wall LGE, ring-like patterns, and LGE involving both ventricles may indicate a higher-risk substrate.[10,12,29] Conversely, limited subepicardial inferolateral LGE, particularly in patients with infarct-like myocarditis, preserved LVEF,

absence of ventricular arrhythmias, and clinical recovery, is generally considered a lower-risk pattern, although not entirely benign.[1,2]

The timing of CMR is also important. In the acute phase, LGE may coexist with edema and active inflammation, and its prognostic meaning may differ from that of persistent LGE after clinical recovery. Persistent LGE on follow-up CMR may represent residual scar and can provide a substrate for late scar-related re-entry. Therefore, repeat CMR after the acute phase may be useful in selected patients, especially those with arrhythmic presentation, persistent symptoms, reduced ventricular function, or initial extensive LGE.[1,2] At present, no universally accepted quantitative LGE threshold mandates ICD implantation, and LGE should be interpreted together with ventricular function, arrhythmic phenotype, clinical presentation, and genetic background.[1]

10.3. ARRHYTHMIC MARKERS. The type and timing of arrhythmia provide important prognostic information. Sustained ventricular tachycardia, ventricular fibrillation, resuscitated cardiac arrest, unexplained syncope, frequent ventricular ectopy, and non-sustained ventricular tachycardia should all prompt careful risk assessment. Polymorphic ventricular tachycardia or ventricular fibrillation during the acute inflammatory phase may reflect transient electrical instability related to edema and inflammation. In contrast, sustained monomorphic ventricular tachycardia, particularly after resolution of acute inflammation, suggests a fixed scar-related substrate and may identify patients at higher risk of recurrence.[1,7-9]

10.4. ELECTROPHYSIOLOGICAL STUDY. The role of electrophysiological study in myocarditis is not fully established. Programmed ventricular stimulation is generally not recommended as a routine test during the acute inflammatory phase, when arrhythmias may be transient and related to active inflammation. However, EPS may be considered after the acute phase in selected patients with persistent LGE, unexplained syncope, non-sustained ventricular tachycardia, frequent ventricular ectopy, or suspected scar-related monomorphic ventricular tachycardia.[1,20,32] Inducible sustained monomorphic ventricular tachycardia may support the presence of a stable re-entry substrate and can contribute to decisions regarding ICD implantation or catheter ablation. Nevertheless, a negative EPS does not exclude future arrhythmic risk, particularly in patients with extensive scar, reduced ventricular function, or pathogenic cardiomyopathy-associated variants. EPS should therefore be considered an adjunct to, rather than a replacement for, multiparametric risk stratification.[1]

Overall, patients at highest risk are those with a combination of adverse features: life-threatening ventricular arrhythmias at presentation, persistent LVEF reduction, extensive or septal LGE, recurrent non-sustained or sustained ventricular tachycardia, unexplained syncope, inducible sustained ventricular tachycardia, right ventricular involvement, or a pathogenic variant associated with arrhythmogenic or dilated cardiomyopathy. In contrast, patients with preserved ventricular function, limited non-septal LGE, absence of complex ventricular arrhythmias, and complete clinical recovery may be managed with close follow-up rather than early device implantation.

11. SPECIAL PHENOTYPES

Certain forms of myocarditis carry particularly high arrhythmic risk. Giant cell myocarditis is associated with aggressive disease progression and a high incidence of ventricular arrhythmias.[33] Immune-mediated myocarditis related to cancer therapy has emerged as an important clinical entity associated with malignant arrhythmias.[34]

Athletes represent a clinically important population in arrhythmic myocarditis because myocarditis is a recognized cause of SCD during sport, particularly in young individuals.[1,16] Exercise during active myocardial inflammation may increase arrhythmic vulnerability through heightened adrenergic tone, increased myocardial oxygen demand, mechanical stress, cytokine-mediated electrical instability, and worsening of inflammatory injury. For this reason, suspected or confirmed myocarditis should lead to immediate restriction from competitive sport and high-intensity exercise.[1,2]

Return-to-play decisions should be individualized and based on resolution of the acute inflammatory process and reassessment of arrhythmic risk. In general, athletes should avoid competitive sport for at least 1 month according to 2025 ESC guidelines[1] and until clinical remission, usually within 3-6 months after myocarditis, with the duration guided by clinical severity, ventricular function, arrhythmic burden, and imaging findings. Before return-to-play, reassessment should include absence of symptoms, normalization of inflammatory markers and cardiac troponin, recovery, or preservation of ventricular function on echocardiography, absence of clinically relevant ventricular arrhythmias on Holter monitoring or exercise testing, and no evidence of ongoing active inflammation.[1] Follow-up CMR may be useful,

particularly in athletes with arrhythmic presentation, initial ventricular dysfunction, extensive LGE, or persistent symptoms[1,2]

Persistent LGE after myocarditis represents a particular challenge. Limited residual LGE in the absence of symptoms, ventricular dysfunction, active inflammation, or ventricular arrhythmias may not necessarily preclude return-to-play, but it should prompt careful shared decision-making and periodic follow-up.[1,2] In contrast, extensive LGE, septal or multifocal LGE, persistent edema, reduced left ventricular ejection fraction, non-sustained or sustained ventricular tachycardia, or unexplained syncope should delay return-to-play and trigger more intensive risk stratification.[1] In selected athletes, genetic testing should also be considered, especially when myocarditis is recurrent, arrhythmic, associated with right ventricular involvement, or accompanied by a family history of cardiomyopathy or SCD, because inflammatory presentations may overlap with arrhythmogenic cardiomyopathy.[1,29-31]

Thus, return-to-play after arrhythmic myocarditis should not be based solely on symptom resolution. A structured approach integrating clinical recovery, biomarkers, ventricular function, rhythm assessment, CMR findings, and, when appropriate, genetic evaluation is essential to reduce the risk of recurrent arrhythmias and SCD.[1]

12. AREAS OF UNCERTAINTY AND CONTROVERSY, KNOWLEDGE GAPS AND FUTURE DIRECTIONS

Despite major advances in the understanding of myocarditis and its arrhythmic manifestations, several important knowledge gaps remain that limit optimal risk stratification and management.

One of the most critical challenges is the **identification of patients at highest risk of malignant ventricular arrhythmias and SCD**.

Although CMR has become central to the diagnostic and prognostic assessment of myocarditis, several aspects of its use for arrhythmic risk stratification remain uncertain. The presence of LGE is consistently associated with myocardial injury, replacement fibrosis, and adverse outcomes; however, the prognostic value of LGE extent, localization, and persistence is less well established. In patients with acute myocarditis and preserved systolic function, the ITAMY study showed that LGE, particularly when involving the mid-wall anteroseptal segments, was associated with worse prognosis.[12] Conversely, other studies have suggested that arrhythmic risk may be driven less by the mere presence of LGE than by its pattern, burden, association with active inflammation, and coexistence with clinical risk markers such as sustained ventricular arrhythmias, syncope, or impaired left ventricular function.[1,13,20,21]

This heterogeneity partly reflects differences in study design and patient populations. Some cohorts enrolled patients with infarct-like myocarditis and preserved ejection fraction, whereas others focused on patients with life-threatening ventricular arrhythmias, reduced ventricular function, or biopsy-proven inflammatory cardiomyopathy. In addition, CMR timing varies substantially across studies. LGE detected during the acute phase may reflect a combination of edema, necrosis, and early fibrosis, whereas persistent LGE after clinical recovery may represent a more stable arrhythmogenic substrate. Therefore, although extensive or septal LGE should be considered a marker of increased risk, no universally accepted quantitative threshold of LGE burden currently mandates a specific therapeutic strategy such as ICD implantation.[1] Serial CMR may help distinguish resolving inflammatory injury from persistent scar, but its incremental prognostic value requires further prospective validation.

A second major controversy concerns the optimal timing of ICD implantation. In patients with sustained ventricular tachycardia, ventricular fibrillation, or resuscitated cardiac arrest, ICD therapy is generally considered for secondary prevention once reversible causes and active inflammation have been addressed.[1,28] However, early ICD implantation during the acute "hot" phase of myocarditis remains debated. On one hand, observational studies have reported a substantial recurrence rate of life-threatening ventricular arrhythmias after hospital discharge, particularly among patients presenting with sustained ventricular tachyarrhythmias.[13,14,21] On the other hand, ventricular dysfunction, edema, and inflammatory electrical instability may improve over weeks to months, and immediate ICD implantation may expose some patients to unnecessary long-term device-related complications.

Current guideline-based approaches therefore favor individualized decision-making according to disease phase and residual risk.[1,2] In the acute inflammatory phase, temporary protection with a wearable cardioverter-defibrillator may be considered for selected high-risk patients, allowing time for recovery and reassessment. After 3-6 months, ICD implantation may be reconsidered in patients with persistent left ventricular dysfunction, recurrent or inducible ventricular tachyarrhythmias, unexplained syncope, extensive or persistent LGE, or evidence of an underlying genetic cardiomyopathy.[1] This

approach attempts to balance the risk of preventable SCD against the possibility of recovery after resolution of myocardial inflammation. Nevertheless, the evidence base remains largely observational, and randomized data defining the optimal timing of ICD implantation in arrhythmic myocarditis are lacking.

Future studies should clarify which **clinical, imaging, and electrophysiological markers** can reliably identify patients who benefit from **early ICD implantation** versus those who can be safely managed with temporary strategies such as wearable cardioverter-defibrillators.

The **role of genetic testing** in patients with arrhythmic myocarditis is another evolving field. Increasing evidence suggests that pathogenic variants associated with inherited cardiomyopathies, particularly in genes encoding desmosomal or cytoskeletal proteins, may predispose patients to arrhythmic myocarditis and influence long-term ventricular remodeling.[29-31] However, the **optimal indications for genetic testing and its integration into clinical risk stratification algorithms** remain to be established. Future studies should investigate whether the identification of pathogenic variants can help refine arrhythmic risk prediction and guide management strategies.

Finally, the **long-term arrhythmic risk after apparent recovery from acute myocarditis** remains incompletely understood. Although many patients experience normalization of ventricular function and resolution of symptoms, myocardial fibrosis may persist and potentially serve as a substrate for late ventricular arrhythmias. Long-term follow-up studies are therefore needed to determine the **true incidence of delayed arrhythmic events and the prognostic significance of residual myocardial scar**.

Addressing these knowledge gaps will require **large prospective registries, multicenter collaborations, and randomized clinical trials** aimed at integrating clinical, imaging, electrophysiological, and genetic data. Such efforts are essential to develop **robust and individualized risk stratification strategies** and to optimize the prevention of SCD in patients with myocarditis.

13. CONCLUSIONS

Arrhythmic myocarditis represents a clinically relevant phenotype associated with increased risk of ventricular arrhythmias and SCD. Although most patients experience an uncomplicated course, a substantial minority develop malignant arrhythmias requiring specialized management. Risk stratification requires integration of clinical presentation, ventricular function, arrhythmic burden, and CMR findings. Improved understanding of arrhythmogenic mechanisms and development of robust risk prediction models will be essential to optimize prevention of SCD in myocarditis.

Future risk stratification should move beyond the binary presence or absence of LGE and incorporate LGE burden, distribution, persistence over time, ventricular function, arrhythmic phenotype, electrophysiological findings, and genetic background to guide individualized decisions regarding temporary protection and ICD implantation.

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