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2019 HRS Expert Consensus Statement on Evaluation, Risk Stratification, and Management of Arrhythmogenic Cardiomyopathy

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Developed in collaboration, endorsement pending, with the American College of Cardiology (ACC), the American Heart Association (AHA), the American Society of Echocardiography (ASE), the Asia Pacific Heart Rhythm Society (APHRS), the European Heart Rhythm Association (EHRA), the Heart Failure Society of America (HFSA), the International Society for Heart & Lung Transplantation (ISHLT), the Japanese Heart Rhythm Society (JHRS), the Latin American Heart Rhythm Society (LAHRS), the National Society of Genetic Counselors (NSGC), the Pediatric & Congenital Electrophysiology Society (PACES), and the Sociedade Brasileira de Arritmias Cardíacas (SOBRAC).

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Abbreviations: **ACC**, American College of Cardiology; **ACCF** = American College of Cardiology Foundation; **ACE**, angiotensin-converting enzyme; **ACM**, arrhythmogenic cardiomyopathy; **ACMG**, American College of Medical Genetics and Genomics; **AHA**, American Heart Association; **AJ**, adherens junction; **ALVC**, arrhythmogenic left ventricular cardiomyopathy; **AP**, action potential; **APHRS**, Asia Pacific Heart Rhythm Society; **ARB**, angiotensin receptor blocker; **ARVC**, arrhythmogenic right ventricular cardiomyopathy; **ASE**, American Society of Echocardiography; **AV**, atrioventricular; **BrS**, Brugada syndrome; **COR**, Class of Recommendation; **CPVT**, catecholaminergic polymorphic ventricular tachycardia; **CRBBB**, complete right bundle branch block; **CT**, computed tomography; **DCM**, dilated cardiomyopathy; **ECG**, electrocardiogram; **EHRA**, European Heart Rhythm Association; **EPS**, electrophysiological study; **ESC**, European Society of Cardiology; **FAO**, fatty-acid oxidation; **GJ**, gap junction; **GUS**, genes of uncertain significance; **HCM**, hypertrophic cardiomyopathy; **HFmrEF**, heart failure with mid-range ejection fraction; **HFrEF**, heart failure with reduced ejection fraction; **HFSA**, Heart Failure Society of America; **HR**, hazard ratio; **HRS**, Heart Rhythm Society; **ICCD**, isolated cardiac conduction disease; **ICD**, implantable cardioverter defibrillator; **ID**, intercalated disc; **IF**, intermediate filament; **ISHLT**, International Society for Heart & Lung Transplantation; **JHRS**, Japanese Heart Rhythm Society; **JUP**, junction plakoglobin; **KSS**, Kearns-Sayre syndrome; **LAHRS**, Latin American Heart Rhythm Society; **LBBB**, left bundle branch block; **LDB3**, LIM domain binding 3; **LGE**, late gadolinium enhancement; **LM**, lateral membrane; **LOE**, Level of Evidence; **LQT1**, long QT syndrome type 1; **LQT3**, long QT syndrome type 3; **LQTS**, long QT syndrome; **LTCC**, L-type calcium channel; **LV**, left ventricular; **LVEF**, left ventricular ejection fraction; **LVNC**, left ventricular noncompaction; **MELAS**, mitochondrial encephalopathy, lactic acidosis, and stroke; **MERRF**, myoclonic epilepsy with ragged red fibers; **MET**, metabolic equivalent; **MLP**, muscle LIM

protein; **MRI**, Magnetic resonance imaging; **NCX**, Na^{+}/Ca^{2+} exchanger; **NGS**, next-generation sequencing; **NSGC**, National Society of Genetic Counselors; **NSVT**, nonsustained ventricular tachycardia; **NYHA**, New York Heart Association; **PACES**, Pediatric & Congenital Electrophysiology Society; **PFHB1**, progressive familial heart block type 1; **PICO**, Population, Intervention, Comparison, Outcome; **PVC**, premature ventricular contraction; **RBBB**, right bundle branch block; **RCM**, restrictive cardiomyopathy; **RV**, right ventricular; **RVEF**, right ventricular ejection fraction; **RVOT**, right ventricular outflow tract; **SCD**, sudden cardiac death; **SOBRAC**, Sociedade Brasileira de Arritmias Cardíacas; **SQTS**, short QT syndrome; **SR**, sarcoplasmic reticulum; **TAD**, terminal activation duration; **TRPM4**, transient receptor potential melastatin 4; **TWI**, T wave inversion; **VF**, ventricular fibrillation; **VFL**, ventricular flutter; **VT**, ventricular tachycardia; **VUS**, variant of uncertain significance; **WES**, whole exome sequencing; **WGS**, whole genome sequencing; **ZASP**, Z-band alternatively spliced PDZ-motif

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Abstract:

Arrhythmogenic cardiomyopathy (ACM) is an arrhythmogenic disorder of the myocardium not secondary to ischemic, hypertensive or valvular heart disease. ACM incorporates a broad spectrum of genetic, systemic, infectious, and inflammatory disorders. This designation includes, but is not limited to, arrhythmogenic right/left ventricular cardiomyopathy, cardiac amyloid and sarcoidosis, Chagas' disease and left ventricular noncompaction. The ACM phenotype overlaps with other cardiomyopathies, particularly dilated cardiomyopathy with arrhythmia presentation which may be associated with ventricular dilatation and/or impaired systolic function. This expert consensus statement provides the clinician with guidance on evaluation and management of ACM and includes clinically relevant information on genetics and disease mechanisms. PICO (Patient, Intervention, Comparison, Outcome) questions were utilized to evaluate contemporary evidence and provide clinical guidance related to exercise in arrhythmogenic right ventricular cardiomyopathy. Recommendations were developed and approved by an expert writing group, after a systematic literature search with evidence tables, and discussion of their own clinical experience, to present the current knowledge in the field. Each recommendation is presented using the Class of Recommendation and Level of Evidence system formulated by the ACC and AHA and is accompanied by references and explanatory text, to provide essential context. The ongoing recognition of the genetic basis of ACM provides the opportunity to examine the diverse triggers and potential common pathway for the development of disease and arrhythmia.

Section 1 Introduction

This international consensus statement is intended to help cardiologists and other health care professionals involved in the care of adult and pediatric patients with arrhythmogenic cardiomyopathy, which encompasses a broad range of disorders, by providing recommendations for evaluation and management and supporting shared decision making between health care providers and patients in a document format that is also useful at the point of care.

This consensus statement was written by experts in the field chosen by the Heart Rhythm Society (HRS) and collaborating organizations. Twelve societies collaborated with the HRS in this effort: the American College of Cardiology (ACC), American Heart Association (AHA), Asia Pacific Heart Rhythm Society (APHRS), American Society of Echocardiography (ASE), European Heart Rhythm Association (EHRA), Heart Failure Society of America (HFSA), International Society for Heart & Lung Transplantation (ISHLT), Japanese Heart Rhythm Society (JHRS), Latin American Heart Rhythm Society (LAHRS), National Society of Genetic Counselors (NSGC), Pediatric & Congenital Electrophysiology Society (PACES), and Sociedade Brasileira de Arritmias Cardíacas (SOBRAC).

In accordance with the policies of the HRS, disclosure of any relationships with industry and other entities was required from the writing committee members (Appendix 1) and from all peer reviewers (Appendix 2). Of the 30 committee members, 16 (53%) had no relevant relationships with industry, including the document Chair and Vice-Chair. Sections that contain recommendations were written by committee members who were free of any relevant relationships with industry.

The writing committee reviewed evidence gathered by electronic literature searches (MEDLINE/PubMed, Embase, Cochrane Library). No specific year was chosen for the oldest literature. Search terms included but were not limited to the following: arrhythmogenic right ventricular cardiomyopathy (ARVC), arrhythmogenic cardiomyopathy (ACM), dilated cardiomyopathy (DCM), lamin, ventricular tachycardia (VT), ventricular arrhythmia, Fabry, noncompaction, phospholamban, cardiac amyloidosis, amyloid heart, heart failure, right ventricular (RV) failure, ARVC therapy, ARVC amiodarone, ARVC sotalol, ARVC flecainide, ablation, family screening, family risk, family member, relative, and electrocardiography.

Evidence tables were constructed to describe the evidence, including study type, with observational cohorts representing the predominant form of evidence. Case reports were not used to support recommendations. This document also used a PICO (Patient, Intervention, Comparison, Outcome) question to focus the search for evidence in section 3.15. A member of the writing committee, free of relationships with industry and educated in evidenced-based medicine and clinical practice document methodology, oversaw the evaluation of the evidence and determination of the Level of Evidence (LOE) for each recommendation.

Recommendations were formulated using the Class of Recommendation (COR) and LOE system formulated by the ACC and AHA (Figure 1). This system provides a transparent mechanism to judge benefit relative to risk using a classification scheme (I, IIa, IIb, and III), supported by evidence quality and quantity using an LOE rating (A, B-R, B-NR, C-LD, C-EO); all recommendations are listed with a COR and LOE rating. For clarity and usefulness, each recommendation contains the specific references from the literature used to justify the LOE rating, which are also summarized in the evidence tables (Appendix 3). Recommendations based solely on the writing committee opinion are given an LOE rating of C-EO. Each recommendation is accompanied by explanatory text or knowledge "byte." Flow diagrams and appropriate tables provide a summary of the recommendations, intended to assist health care providers at the point of care. A comprehensive discussion (Section 4) is presented to further the understanding of molecular mechanisms underlying ventricular dysfunction and arrhythmogenesis in ACM. For additional information on HRS clinical practice document development, please refer to the HRS methodology manual.(1) Clinical practice documents that are relevant to this document are listed in Table 1.

To reach consensus, the writing committee members participated in surveys, requiring a predefined threshold of 75% approval for each recommendation, with a quorum of two-thirds of the writing committee. An initial failure to reach consensus was resolved by subsequent discussions, revisions as needed, and re-voting. The mean consensus over all recommendations was 94%.

An industry forum was conducted to achieve a structured dialogue to address technical questions and gain a better understanding of future directions and challenges through a structured dialogue. Because of the potential for actual or perceived bias, HRS imposes strict parameters for information sharing to ensure that industry participates only in an advisory

capacity and has no role in either the writing or review of the document. This consensus statement underwent internal review by the HRS Scientific and Clinical Documents Committee and was approved by the writing committee. Public comment on recommendations was obtained. The document underwent external peer review by reviewers appointed by HRS and each of the collaborating societies, and revisions were made by the chairs.

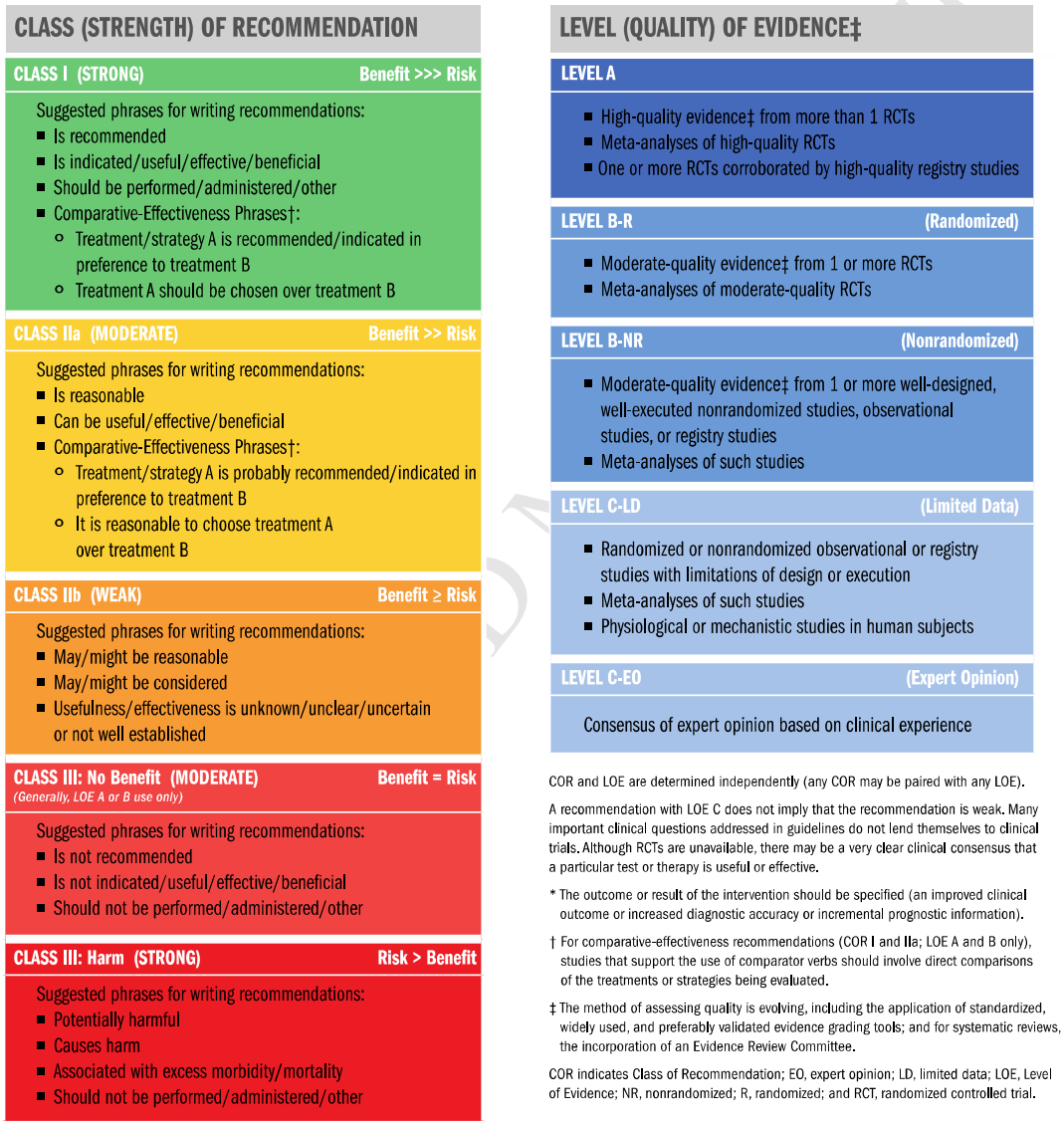


Figure 1. Applying Class of Recommendation and Level of Evidence to clinical strategies, interventions, treatments, and diagnostic testing in patient care.* Reproduced with permission of the American College of Cardiology and the American Heart Association.(2)

Table 1. Relevant Clinical Practice Documents

Title	Organization	Publication Year
2017 AHA/ACC/HRS Guideline for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death(3)	AHA, ACC, HRS	2017
ACC/AHA/HRS 2008 Guidelines for device-based therapy of cardiac rhythm abnormalities: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines(4)	ACC, AHA, HRS	2008
HRS/EHRA expert consensus statement on the state of genetic testing for the channelopathies and cardiomyopathies(5)	HRS, EHRA	2011
HRS/EHRA/APHRS expert consensus statement on the diagnosis and management of patients with inherited primary arrhythmia syndromes(6)	HRS, EHRA, APHRS	2013
2016 ACC/AHA/HFSA focused update on new pharmacological therapy for heart failure: an update of the 2013 ACCF/AHA guideline for the management of heart failure(7)	ACC, AHA, HFSA	2016
2013 ACCF/AHA guideline for the management of heart failure(8)	ACC, AHA	2013
2016 ESC guidelines for the diagnosis and treatment of acute and chronic heart failure(9)	ESC	2016
Marcus et al. Diagnosis of Arrhythmogenic Right Ventricular Cardiomyopathy/Dysplasia. Proposed Modification of the Task Force Criteria(10)	NA	2010
Hershberger et al. Genetic evaluation of cardiomyopathy - A Heart Failure Society of America Practice Guideline(11)	HFSA	2018
Corrado et al. Treatment of Arrhythmogenic Right Ventricular Cardiomyopathy/Dysplasia. An International Task Force Consensus Statement(12)	NA	2015

Section 2 Arrhythmogenic Cardiomyopathy

2.1 Arrhythmogenic Cardiomyopathy

Arrhythmogenic cardiomyopathy (ACM) is defined as an arrhythmogenic heart muscle disorder not explained by ischemic, hypertensive, or valvular heart disease. ACM may present clinically as symptoms or documentation of atrial fibrillation, conduction disease, and/or right ventricular (RV) and/or left ventricular (LV) arrhythmia (Figure 2).

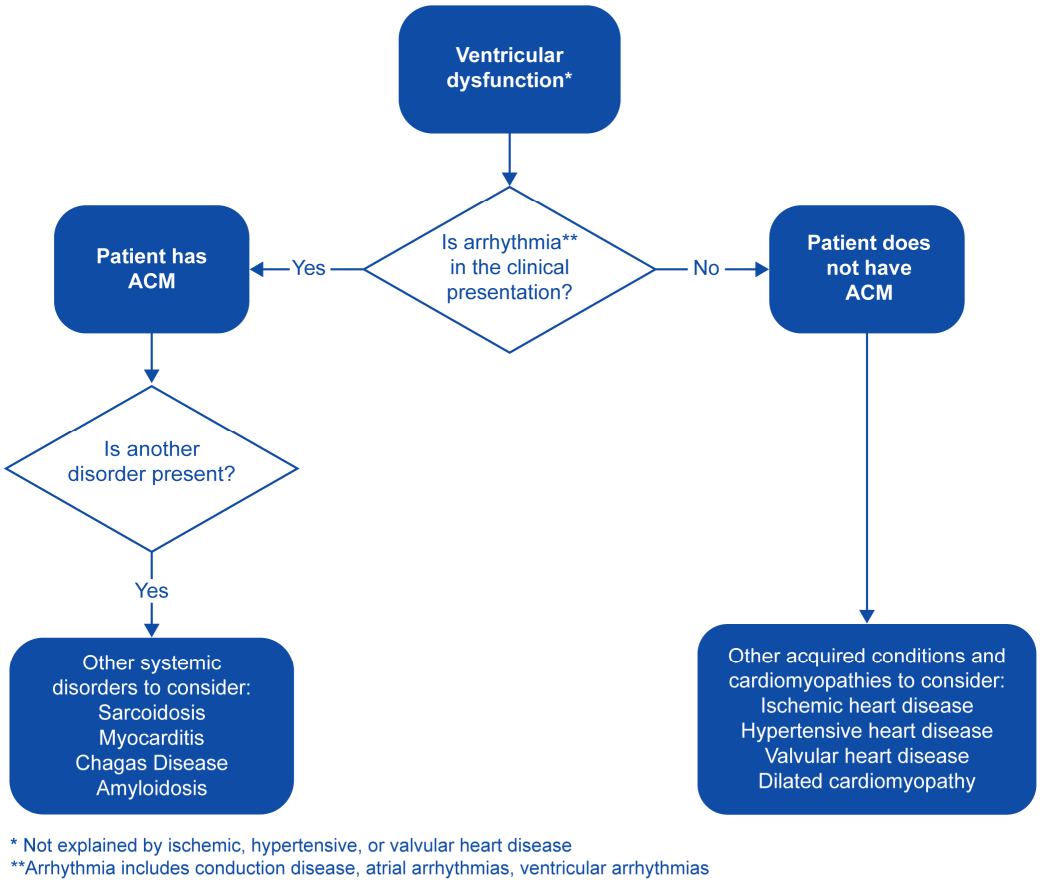


Figure 2. Algorithm to consider the presence of an arrhythmogenic cardiomyopathy (ACM).

The etiology may be part of a systemic disorder (eg, sarcoidosis, amyloidosis), an apparently isolated cardiac abnormality (eg, myocarditis), an infection (eg, Chagas disease), or be genetic (eg, desmosomal ARVC or arrhythmogenic left ventricular cardiomyopathy [ALVC], lamin A/C, filamin-C, phospholamban) with particular phenotypic (cardiac, cutaneous, immunologic) features (Figure 3). Ion channel disease, which can also cause ACM, is considered in Section 4

Disease Mechanisms and is discussed in other clinical practice documents. Similarly, sarcoidosis and Chagas disease, which are important causes of ACM, are discussed only briefly because they are the subject of other clinical practice documents. In contrast, the arrhythmic management of patients with amyloidosis is comprehensively discussed in Section 5.1, since this topic has not been adequately addressed in previous clinical practice documents.

A distinguishing feature of ACM is the clinical presentation with documented and/or symptomatic arrhythmia. The ACM phenotype can overlap with other cardiomyopathies, particularly DCM, in which the arrhythmia presentation may be associated with moderate to severe ventricular dilatation and/or impaired systolic function (eg, ARVC or ALVC caused by *desmoplakin, filamin C, SCN5A* or *phospholamban* variants) (Figure 3 and Figure 4). As with all forms of genetically based cardiovascular disease, the mechanisms responsible for the phenotype that develops rely on dysfunction of final common protein pathways. For instance, DCM is typically caused by variants in genes encoding structural proteins such as cytoskeletal and sarcomeric proteins and, in this case, usually presents with features of HF. Arrhythmias, which are most commonly caused by variants in genes encoding ion channels when isolated, may also be a late manifestation in DCM or other forms of cardiomyopathy. These “final common pathways” can interact as overlapping pathways through protein-protein binding and, in these cases, can provide complex phenotypes, such as DCM with significant arrhythmia potential. This distinction between an arrhythmic vs a HF presentation in patients who fulfill current DCM diagnostic criteria is important because the genetic basis, sudden death risk, prognosis, and focus of management are different in these two scenarios. Although rare, ACM can also overlap with hypertrophic cardiomyopathy (HCM; final common pathway, the sarcomere), restrictive cardiomyopathy (RCM; final common pathway, the sarcomere), or LV noncompaction (LVNC; final common pathway, the sarcomere and cytoskeleton). Troponin T variants, unlike other sarcomeric disease-causing genes, may present with cardiac arrest or sudden death despite mild or even absent left ventricular hypertrophy, whereas troponin I variants may cause a restrictive phenotype in which the dominant clinical presentation is atrial fibrillation.(13-15) Nonsarcomeric HCM (eg, Anderson-Fabry disease), caused by alpha-galactosidase A variants, may also initially present with arrhythmia, though not in the absence of diagnostic phenotypic features.

Clinical evaluation to diagnose and manage ACM in adults and children should consider genetic and nongenetic causes with an assessment of electrocardiographic and structural abnormalities and arrhythmic risk. The pedigree evaluation should include a 3-generation family tree with an emphasis on premature cardiovascular events (eg, sudden death, HF) and associated cardiac (eg, arrhythmias, conduction disease) and noncardiac (eg, skeletal myopathy, renal failure, auditory/visual defects) phenotypes. Mutation analysis, endomyocardial biopsy, and electrophysiology studies (EPSs) are indicated in the particular clinical circumstances discussed below.

Genotype	Phenotype
Desmosomal	ARVC/ALVC, hair/skin abnormalities
Lamin A/C	Conduction disease, ventricular arrhythmia/sudden death, DCM, lipodystrophy, muscular dystrophy
SCN5A	Brugada Syndrome, conduction disease, AF, VT/VF, DCM
PLN	Low voltage ECG, VT/VF, DCM, HCM, ARVC
TMEM43	Sudden death M>F, DCM
FLNC	Sudden death, DCM
RBM20	DCM, AF; ventricular arrhythmia/sudden death uncommon as an early feature
Desmin	Skeletal myopathy, DCM; arrhythmia uncommon as an early feature

Figure 3. Arrhythmogenic cardiomyopathy (ACM): phenotypes associated with the most common genetic causes of ACM. ALVC=arrhythmogenic left ventricular cardiomyopathy; ARVC=arrhythmogenic right ventricular cardiomyopathy; DCM=dilated cardiomyopathy; ECG=electrocardiogram; F=female; *FLNC*=filamin-C; M=male; HCM=hypertrophic cardiomyopathy; *PLN*=phospholamban; *RBM20*=RNA binding motif protein 20; VF=ventricular fibrillation; VT=ventricular tachycardia; *SCN5A*=sodium voltage-gated channel alpha subunit 5; *TMEM43*=transmembrane protein 43.

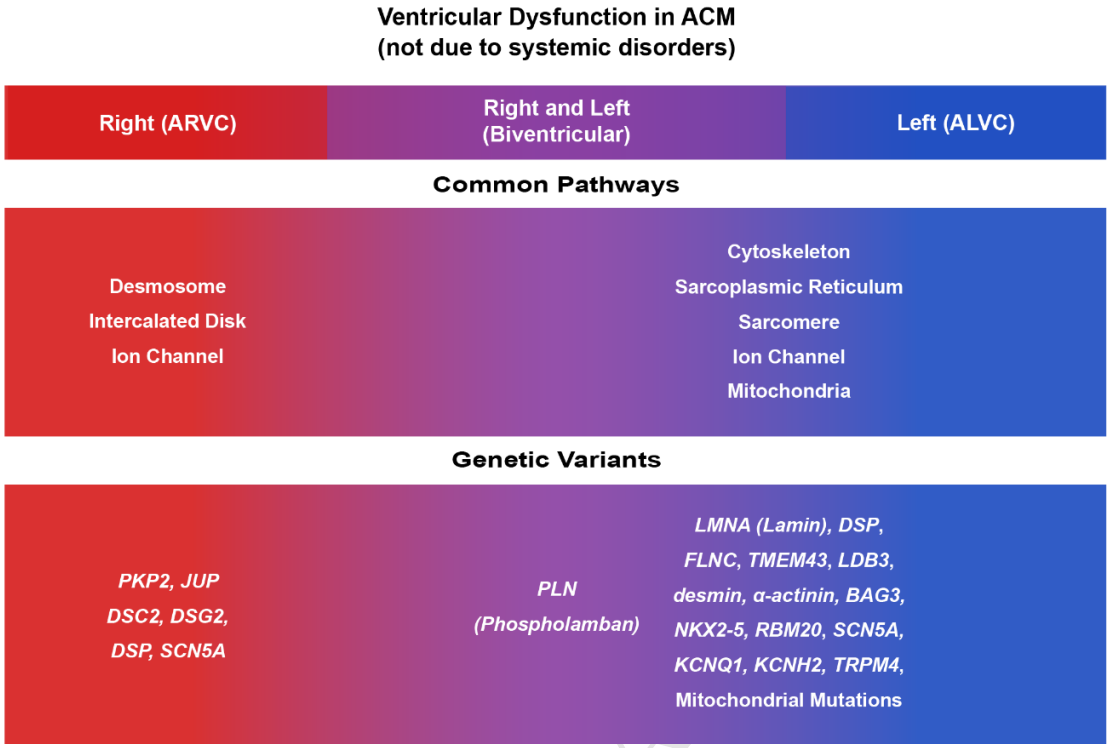


Figure 4. Approach to understanding the common pathway and genetic variants in a patient with arrhythmogenic cardiomyopathy (ACM) according to the predominant ventricular dysfunction. See also Table 3. ALVC=arrhythmogenic left ventricular cardiomyopathy; ARVC=arrhythmogenic right ventricular cardiomyopathy; *BAG3*=BCL2 associated athanogene 3; *DSC2*=desmocollin-2; *DSG2*=desmoglein-2; *DSP*=desmoplakin; *FLNC*=filamin-C; JUP=junction plakoglobin; *KCNH2*=potassium voltage-gated channel subfamily H member 2; *KCNQ1*=potassium voltage-gated channel subfamily Q member 1; *LDB3*=LIM domain binding 3; *LMNA*=lamin A/C; *NKX2-5*= NK2 homeobox 5; *PKP2*=plakophilin-2; *PLN*=phospholamban; *RBM20*=RNA binding motif protein 20; *SCN5A*=sodium voltage-gated channel alpha subunit 5; *TMEM43*=transmembrane protein 43; *TRPM4*=transient receptor potential melastatin 4.

2.2 Arrhythmogenic Right Ventricular Cardiomyopathy

ARVC is the best characterized of the ACMs, with early clinical reports(16-18) leading to internationally agreed-upon diagnostic(10,18,19) and management guidelines.(12) The predominant RV involvement with left bundle branch block (LBBB) VT and fibrous or fibro-fatty replacement of RV myocardium is distinct from the LV predominance of most cardiac conditions and other ACMs. ARVC is most often familial, with autosomal dominant inheritance. Studies of one of the uncommon recessive forms(20,21) with a cardiocutaneous phenotype led to the identification of the first disease-causing gene(22) and the recognition that most ARVC is caused by variants in one of several desmosomal genes (see Genetics, below).(23-26)

Autosomal dominant inheritance predominates and most patients will have one or more pathogenic variants in genes encoding desmosomal proteins. The disease is therefore considered to have desmosome dysfunction as its final common pathway; in other words, ARVC is a disease of the desmosome or desmosomopathy.(27-29) However, there are disease-causing genes that cause "classic" ARVC that do not encode for desmosomal proteins. In most of these cases, the proteins encoded by the mutated gene are either binding partners of desmosomal proteins or proteins whose function is disturbed due to desmosomal protein dysfunction or vice versa, such as ion channels. Recently, pathogenic gene variants have been identified in patients and families, which suggests that more than just the desmosome is involved, but in fact the intercalated disk as a whole is involved.(27-29) LV ACM would similarly follow this "final common pathway" model.(27-29)

2.3 Arrhythmogenic Left Ventricular Cardiomyopathy

The distinctive phenotypic presentation of ARVC with LBBB VT associated with RV structural abnormalities overshadowed recognition that most patients with ARVC develop LV involvement, especially when evaluated with sensitive imaging modalities such as cardiac magnetic resonance imaging (MRI) (biventricular ACM). With the identification of desmosomal disease-causing variants, individuals and families with predominantly LV arrhythmia and structural abnormalities were recognized(30,31), as were patients with nondesmosomal arrhythmia-associated variants (eg, lamin A/C,(32) phospholamban,(33) filamin-C ((34)) who had ACM with predominantly left (but also right) or biventricular phenotypes. The term "ALVC" has been proposed to recognize ACM of LV origin as distinct from ARVC, and to rectify the relative lack of diagnostic and prognostic data, which contrasts with multiple international clinical practice documents(10,12,19) generated for ARVC. In time, a better understanding will hopefully be gained of why particular variants (eg, desmosomal, lamin A/C (LMNA), sodium voltage-gated channel alpha subunit 5 (SCN5A), desmin (DES)) cause diverse phenotypes, and the clinical distinction between ARVC and ALVC will be viewed from a pathogenetic rather than a phenotypic basis under an umbrella of genetic and acquired ACM. For the present, however, defining the diagnostic criteria and phenotypic features of ALVC in relation to outcome will be important in understanding the genetic basis and pathogenesis of the genetic and nongenetic conditions encompassed by ACM.

2.4 Final Common Pathways in Arrhythmogenic Cardiomyopathy

The “final common pathway” hypothesis,(35-37) which states that hereditary cardiovascular diseases with similar phenotypes and genetic heterogeneity will occur due to abnormalities in genes encoding proteins of similar function or genes encoding proteins participating in a common pathway cascade, was initially described in 1998 in an attempt to direct gene discovery for various cardiovascular clinical phenotypes. Since its original description, the “final common pathway” hypothesis has been fairly predictive of the genes and proteins involved in phenotype development and, to a lesser extent, disease severity. This is seen in HCM (a disease of sarcomere function), arrhythmia disorders such as long QT syndrome (LQTS), Brugada syndrome (BrS), catecholaminergic polymorphic ventricular tachycardia (CPVT), and others (a disease of ion channel function), Noonan syndrome (a disease of the Ras pathway). In the case of ARVC, the final common pathway appears to be a disturbance of the function of the desmosome and intercalated disk. However, ACM includes not only ARVC but also arrhythmogenic left-sided cardiomyopathies, which are currently less well studied. However, data do exist that appear to demonstrate pathways that overlap not only with the those associated with ARVC, but also with sarcomere and ion channel pathways. Knowledge of the genes and their encoded proteins involved in the pathophysiology of these disorders, as well as of other proteins that interact with the final common pathway proteins, enables not only a better understanding of the clinical phenotypes that develop but also provides potential targets for current and future therapies (Figure 5 and Figure 18).

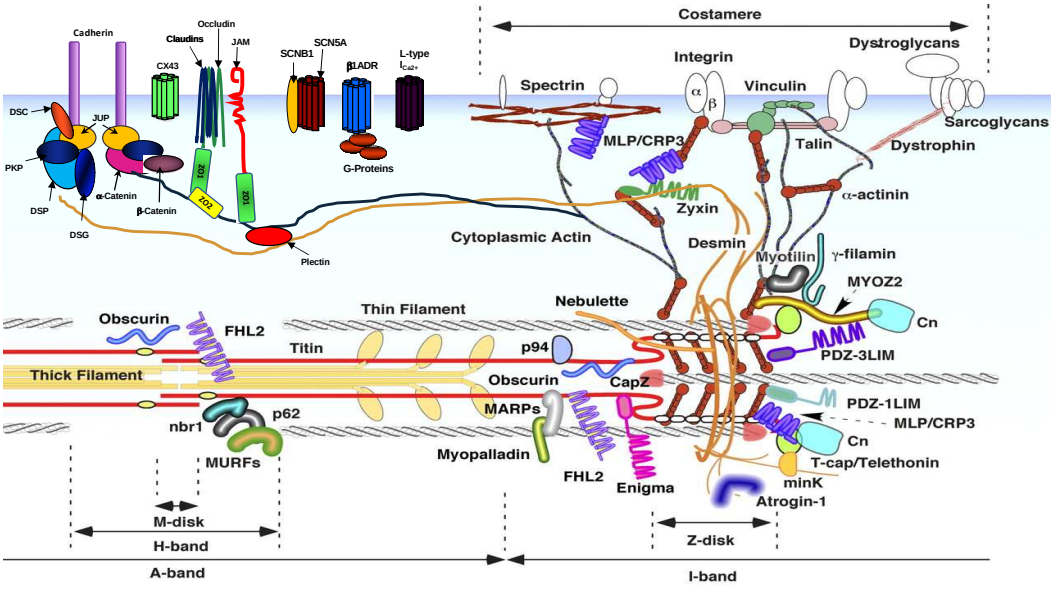


Figure 5. Cytoskeletal protein complexes within the cardiomyocyte costamere and Z-disk. Force is distributed externally from the costameres and internally throughout the myocyte by the Z-disk. Structural and signaling proteins within the costamere and Z-disk are shown. Many of these proteins have been implicated in mechano-sensing or sarcomere assembly. MYOZ2=myozenin 2; Cn=calcineurin; PDZ-3LIM=one-PDZ and three-LIM domain protein; PDZ-1LIM=one-PDZ and one-LIM domain protein; MLP/CRP3=muscle-specific LIM protein/cysteine-rich protein 3; FHL2=four-and-a-half LIM protein 2; MAPRs=muscle ankyrin repeat proteins; MURFs=muscle-specific ring-finger proteins. Modified from Hoshijima (38)

Section 3 Diagnosis and Treatment of Arrhythmogenic Cardiomyopathy

3.1 Diagnosis of Arrhythmogenic Cardiomyopathy

The clinical presentation and diagnosis of the genetically determined causes (eg, ARVC, lamin A/C, filamin-C, desmin) of ACM prior to puberty is uncommon. The diagnosis of ACM requires a high degree of clinical suspicion concomitant with diagnostic testing. Clinical perspectives of ACM arise primarily from experiences with patients who present with arrhythmias of RV origin, as well as sudden cardiac death (SCD).(39) In the subset of ARVC patients, individual clinical and diagnostic findings are individually neither highly specific nor sensitive, and diagnostic criteria have been established to standardize the diagnosis.(10,19) The diagnosis of ARVC should be considered in the following: patients with exercise-related palpitations and/or syncope; survivors of sudden cardiac arrest (particularly during exercise); and individuals with frequent ventricular premature beats (>500 in 24 hours) and/or VT of LBBB morphology in the absence of

other heart disease.(10,19,39,40) In patients with suspected ACM who do not meet the diagnostic criteria for ARVC, the evaluation should be systematic to establish the diagnosis of other genetic and nongenetic forms of ACM, with repeated evaluations considered if the disease is strongly suspected.

3.2 Evaluation Overview

The underlying principles and clinical evaluations required for the diagnosis and management of ACM are similar in ARVC and ALVC with respect to excluding acquired causes for the cardiomyopathy, ensuring a probable or definitive diagnosis and characterizing arrhythmia in relation to treatment and prognosis. Genetic causes of isolated or predominantly RV arrhythmia and structural abnormalities are most commonly associated with desmosomal gene variants. There may be additional cutaneous phenotypes that manifest with autosomal dominant *desmoplakin* variants and are often florid in recessive desmosomal disease.(20,23) The genetic causes of arrhythmia and structural disease of LV origin however, typically manifest with additional cardiac (eg, conduction disease, atrial fibrillation) or systemic (eg, muscular dystrophy, lipodystrophy) phenotypes. Familial evaluation should therefore focus on arrhythmic disease, but also consider associated phenotypes. Several of the ALVC disease-causing gene variants have been reported in patients with LV or biventricular arrhythmia and LV dilatation and/or impaired function (eg, *PLN, FLNC, LMNA, SCN5A*). The diagnostic distinction here is from DCM and its genetic causes.(28,41,42) In ACM, the clinical presentation in the proband and/or family members is typically with arrhythmia rather than heart failure, although both may be present in advanced disease.

In patients with suspected ACM, the initial evaluation includes clinical history, physical examination, detailed family history, 12-lead electrocardiogram (ECG), 2D echocardiography, ambulatory ECG monitoring and cardiac MRI.(10) Most patients with suspected ACM presenting with arrhythmia can be diagnosed using noninvasive imaging and electrocardiographic assessment. If the initial testing is nondiagnostic, additional testing may include signal-averaged ECG, exercise ECG, pharmacological testing with isoproterenol,(43) endomyocardial biopsy, and EPS. In a series of 48 older children (aged 13–15 years) presenting with possible ACM, a comprehensive clinical and genetic evaluation in the context of the adult Task Force Criteria for the diagnosis of ARVC revealed that 46% of the children had features consistent with a diagnosis of HCM, DCM, or ion channel disease, while 25% had features consistent with ARVC.(44)

The diagnosis of ALVC relies on documenting arrhythmia of isolated or predominantly LV origin in a proband or family member with cardiomyopathy (eg, arrhythmia) not caused by ischemic, valvular, or hypertensive heart disease. Impaired LV function and/or structural abnormalities as determined by 2D ECG and Cardiac MRI can be absent, mild, or severe. Typically, arrhythmia is an early manifestation of disease. Internationally accepted diagnostic criteria analogous to those established for ARVC(10) are required; however, an issue is the diagnosis of ACM in the presence of other potential causes for which coexistence vs causality may be difficult to determine. Given the currently incomplete knowledge of the genetic basis of ACM, particularly of the ALVC and biventricular forms, the development of clinical diagnostic criteria is needed.

After the original clinical description of RV dysplasia(17) it became clear that the diagnosis of this condition would be difficult to establish, particularly in the early stages of the disease when RV dilation or segmental dilatation is mild. Therefore, differentiating RV dysplasia from the normal heart could be equivocal. A task force was subsequently assembled to consider criteria for the diagnosis of arrhythmogenic RV dysplasia/cardiomyopathy, the results of which were published in 1994.(19) The task force concluded that there is no single gold standard for the diagnosis and that disease and the diagnosis require a combination of major and minor criteria encompassing structural, histological, electrocardiographic, arrhythmogenic, and genetic factors. LV disease was excluded from these criteria. The revision of the Task Force Criteria in 2010 included LV disease and added cardiac MRI (CMR) for the diagnosis; the criteria are listed in Figure 6.(10) Diagnostic criteria for ARVC in the pediatric population remain to be established since disease expression in children is uncommon. In a series of 16 patients, clinical presentation was with life-threatening arrhythmia in 10 (median age of 14 years). In all 16 patients, LV and/or RV dysfunction was common and associated with the histopathological features of ARVC.(45) Recently, a diagnostic and prognostic role has been proposed for the presence of anti-desmoglein-2 (DSG2) antibodies, which were present in ARVC patients but not in controls; this work is potentially important and warrants confirmation in a larger number of patients and in other forms of ACM (eg, cardiac sarcoidosis).(46,47)

Modified Task Force Criteria for ARVC – Diagnostic Categories Major and Minor Criteria		
Definite: 2 major OR 1 major and 2 minor, OR 4 minor criteria from different categories Borderline: 1 major and 1 minor, OR 3 minor criteria from different categories Possible: 1 major, OR 2 minor criteria from different categories		
	Major	Minor
Global or regional dysfunction and structural alterations determined by echo, MRI or RV angiography:		
Echo	Regional RV akinesia, dyskinesia, or aneurysm and 1 of the following (end diastole): a) PLAX RVOT ≥32 mm (PLAX/BSA ≥ 19mm/m^2) b) PSAX RVOT ≥36 mm (PSAX/BSA ≥ 21mm/m^2) c) Fractional area change ≤ 33%	Regional RV akinesia, dyskinesia, or aneurysm and 1 of the following (end diastole): a) PLAX RVOT ≥29 mm to <32 mm (PLAX/BSA ≥16 to <19 mm/m^2) b) PSAX RVOT ≥32 to <36 mm (PSAX/BSA ≥18 to <21 mm/m^2) c) Fractional area change >33 to ≤40%
MRI	Regional RV akinesia or dyskinesia or dyssynchronous RV contraction and 1 of following: a) Ratio RVEDV/BSA ≥110 mL/m^2 (male), ≥100 mL/m^2 (female) b) RVEF ≤40%	Regional RV akinesia or dyskinesia or dyssynchronous RV contraction and 1 of following: a) Ratio RVEDV/BSA ≥100 to <110 mL/m^2 (male), ≥90 to 100 mL/m^2 (female) b) RVEF >40 to ≤45%
RV angiography	Regional RV akinesia, dyskinesia, or aneurysm	
Tissue characterization of wall		
Endomyocardial biopsy showing fibrous replacement of the RV free wall myocardium in ≥1 sample, with or without fatty replacement and with:	Residual myocytes <60% by morphometric analysis (or <50% if estimated)	Residual myocytes 60% to 75% by morphometric analysis (or 50% to 65% if estimated)
Repolarization Abnormalities		
ECG	Inverted T waves in right precordial leads (V_1, V_2, and V_3) or beyond in individuals >14 years of age (in the absence of complete RBBB QRS ≥120ms)	I. Inverted T waves in leads V_1 and V_2 in individuals >14 years of age (in the absence of complete RBBB) or in V_4, V_5, or V_6. II. Inverted T waves in leads V_1, V_2, V_3 and V_4 in individuals >14 years of age in the presence of complete RBBB
Depolarization/conduction abnormalities		
ECG	Epsilon wave (reproducible low-amplitude signals between end of QRS complex to onset of the T wave) in the right precordial leads (V_1 to V_3)	I. Late potentials by SAECG in ≥1 of 3 parameters in the absence of QRS duration of ≥110ms on the standard ECG: a) Filtered QRS duration (fQRS) ≥114 ms b) Duration of terminal QRS <40 µV (low-amplitiude signal duration) ≥38 ms c) Root-mean-square voltage of terminal 40 ms ≤20 µV II. Terminal activation duration of QRS ≥55 ms measured from the nadir of the S wave to the end of the QRS, including R' in V_1, V_2, or V_3 in the absence of complete RBBB
Arrhythmias		
	Nonsustained or sustained VT of LBBB with superior axis (negative or indeterminate QRS in leads II, III, and aVF and positive in lead aVL)	I. Nonsustained or sustained VT or RV outflow configuration, LBBB morphology with inferior axis (positive QRS in II, III and aVF and negative in lead aVL) or of unknown axis II. >500 ventricular extrasystoles per 24 hours (Holter)
Family history		
	I. ARVC confirmed in a first-degree relative who meets current Task Force Criteria II. ARVC confirmed pathologically at autopsy or surgery in a first-degree relative III. Identification of a pathogenetic mutation categorized as associated or probably associated with ARVC in the patient under evaluation	I. History of ARVC in a first-degree relative in whom it is not possible or practical to determine whether the family member meets current Task Force Criteria II. Premature sudden death (<35 years of age) due to suspected ARVC in a first-degree relative III. ARVC confirmed pathologically or by current Task Force Criteria in second-degree relative

Figure 6. Modified task force criteria for Arrhythmogenic right ventricular cardiomyopathy (ARVC) showing the diagnostic categories for major and minor criteria according to the 2010 ARVC Task Force criteria. BSA=body surface area; ECG=electrocardiogram; MR=magnetic resonance imaging; QLS=PLAX=parasternal long-axis; PSAX=parasternal short-axis; RBBB=right bundle branch block; RV=right ventricular, RVEDV=right ventricular end-diastolic volume; RVEF=right ventricular ejection fraction; RVOT=right ventricular outflow tract; SAECG=signal-averaged electrocardiogram. These criteria are sensitive and specific in differentiating ARVC patients from control populations but have not been adequately tested in relation to other ACMs with overlapping phenotypes (eg, cardiac sarcoidosis, myocarditis).(48)

3.3 Family History

A detailed family history covering at least 3 generations and the clinical evaluation of relatives are important in the diagnostic assessment for ACM. In a patient with suspected ACM, a family history focusing on unexplained premature deaths, arrhythmias, and conduction disease may identify familial disease. The presence of associated noncardiac phenotypes (eg, skeletal myopathy, other organ disease) can also provide clues to the underlying diagnosis for both genetic (eg, desmin or lamin myopathy) and nongenetic (eg, Chagas disease) causes.

The 12-lead ECG is an important part of the diagnostic evaluation of patients with suspected ACM. Reports on the ECG findings of patients who meet the diagnostic criteria for ARVC have shown that the majority (>85%) demonstrate at least one characteristic ECG feature of ARVC but a normal ECG has been reported in up to 12%.(49-51) ARVC is a progressive disease, which is reflected in the well-documented dynamic ECG changes associated with disease progression that have been demonstrated in several cohorts of ARVC patients.(49-54) Over time, the ECG may evolve with further prolongation of the S wave upstroke, increased QRS duration, and development of bundle branch block and precordial T wave inversion.(53,54)

3.4 Electrocardiogram Features in Arrhythmogenic Right Ventricular Cardiomyopathy

3.4.1 Repolarization Abnormalities

The prevalence of T wave inversion (TWI) in leads V_1–V_3 (the characteristic ECG finding in patients with ARVC) varies from 19% to 67%,(55-57) presumably due to the difference in study populations. TWI in the precordial leads beyond V2 is relatively common in Afro-Caribbean individuals,(58) although it is rare (1% in females and 0.2 % in males) in asymptomatic white individuals.(59) TWI in patients younger than 14 years of age is more frequently observed in

athletes (the so-called "juvenile pattern").(60) TWI is reasonably specific in patients older than 14 years of age and is considered a major diagnostic abnormality in ARVC. TWI in leads V_1–V_4 in individuals older than 14 years associated with complete right bundle branch block (CRBBB)is a minor criterion for the diagnosis of ARVC (Figure 7). The presence of TWI in lateral and/or inferior leads suggests LV involvement in patients with ARVC (Figure 7).(61)

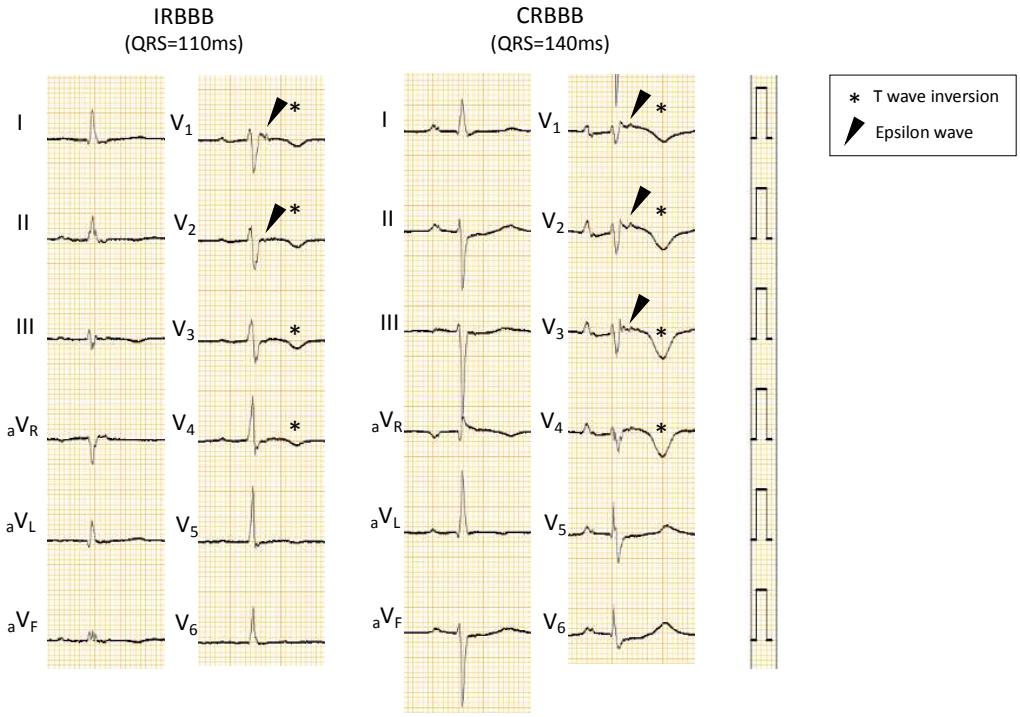


Figure 7. Representative 12-lead ECG obtained from ARVC patients with incomplete right bundle branch block (IRBBB) and complete right bundle branch block (CRBBB). QRS duration of IRBBB and CRBBB was 110 ms and 140 ms, respectively. The closed arrow indicates an epsilon wave, which was defined as low-amplitude deflection located between the end of the QRS and the onset of the T wave in leads V1–V3. The asterisk indicates the T wave inversion recorded in V1–V4 in patients with ARVC and IRBBB or CRBBB. ARVC=arrhythmogenic right ventricular cardiomyopathy; ECG=electrocardiogram.

3.4.2 Depolarization and Conduction Abnormalities

3.4.2.1 Epsilon Wave

The epsilon wave is defined as a reproducible low amplitude deflection located between the end of the QRS and the onset of the T wave in leads V_1–V_3 (Figure 7).(10,56) Epsilon waves reflect delayed conduction in the RV (Figure 7). The prevalence of the epsilon wave in European and

American registries varies from 0.9% to 25%.(62) Electroanatomical mapping in patients with ARVC and an epsilon wave have shown that the timing of the epsilon wave on the surface ECG corresponded to activation of the basal (peri-tricuspid) RV region of the epicardium. Epsilon waves have been associated with severe conduction delay due to extensive endocardial and epicardial scarring at that site.(63) Epsilon waves may reflect short-term arrhythmia risk but are of limited diagnostic utility because they are variable, have low sensitivity and specificity (seen in other conditions), and are dependent on ECG filter setting and magnification.(54,62,64,65)

3.4.2.2 Prolonged Terminal Activation Duration

Prolonged terminal activation duration (TAD) is measured from the nadir of the S wave to the end of all depolarization deflections (Figure 8). A TAD ≥55 ms in any of the V_1–V_3 leads in the absence of CRBBB is defined as a prolonged TAD.(55,66) Prolonged TAD in leads V_1–V_3 has been reported to aid in differentiating ARVC from right ventricular outflow tract (RVOT)-VT.(67) Prolonged TAD was confirmed in 30 of 42 patients with ARVC and in only 1 of 27 patients with idiopathic RVOT-VT.(55) Moreover, TAD prolongation was the sole ECG abnormality in 4 of 7 gene-positive family members with ARVC,(68) suggesting a role in the early recognition of "at-risk" individuals.

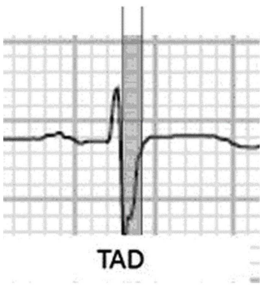


Figure 8. Terminal activation duration (TAD) is measured from the nadir of the S wave to the end of all depolarization deflections and is prolonged if ≥55 ms in any of the V_1–V_3 leads in the absence of CRBBB. Adapted from Nunes de Alencar Neto et al.(69)

3.4.2.3 Electrocardiogram Abnormalities in Arrhythmogenic Cardiomyopathies Other Than Arrhythmogenic Right Ventricular Cardiomyopathy

Characterization of ECG findings in other ACMs is less detailed. The 12-lead ECG abnormalities include inverted T waves in leads I, aVL, and V4-6; other repolarization abnormalities; generalized low-voltage; increased QRS duration; and isolated ectopy of LV origin. A completely normal ECG is uncommon. Variants in *lamin A/C* may be associated with progressive conduction

disease, (eg, PR prolongation to atrioventricular block), variants in desmosomal genes and *phospholamban* with a low-voltage ECG, and in *filamin-C* with minor repolarization changes only. In contrast to ARVC associated with desmosomal variants, ECG abnormalities do not appear to be an early marker of disease in FLNC and desmin-related ACM. In ACMs associated with systemic disease, conduction abnormalities are often early features (eg, sarcoidosis and Chagas disease).(70,71)

3.4.3 Ambulatory Electrocardiogram Monitoring

Ambulatory ECG monitoring (24 to 48 hours) is important for characterizing all patients for whom the diagnosis of ACM is being considered. The presence of >500 ventricular premature beats per 24-hour monitoring period is a minor diagnostic criterion for ARVC. In a study of 40 patients meeting ARVC Task Force Criteria who underwent ambulatory ECG monitoring for an average of 159 hours, the average ventricular premature beat count (per 24 hours) was 1091, with significant day-to-day variation. Despite this variation, the 24-hour burden was accurate 89.6% of the time to the correct grouping based on the revised Task Force Criteria.(72,73)

Documentation of ventricular arrhythmia with a morphology consistent with an LV origin is required for the diagnosis of ALVC. Precise definitions relating to characteristics VT and/or frequency of ventricular ectopy remain to be established for forms of ACM other than ARVC. The arrhythmia may be asymptomatic or associated with palpitations and/or impaired consciousness.

3.4.4 Signal-Averaged Electrocardiogram

Although an abnormal signal-averaged ECG was a minor criterion in the 2010 Task Force Criteria, its use has declined largely due to its limited sensitivity and specificity, as well as its limited availability in many medical centers.(10,74)

3.5 Cardiac Imaging

Echocardiography and other noninvasive imaging modalities are important for evaluating patients suspected of ACM to assess structural and functional abnormalities and aid in diagnosis.(75,76)

For many patients with suspected ACM, 2D echocardiography provides adequate visualization, enabling a systematic qualitative and quantitative assessment of ventricular function and cavity

dimensions, although there may be limitations when imaging the right ventricle. Additional imaging with cardiac MRI provides accurate measurements of volumes and also regional and global ventricular function.(52) If cardic MRI is contraindicated or not available, multidetector computed tomography (CT), RV angiography or radionuclide angiography are alternatives, but are currently less frequently used to assess ventricular function. The Task Force Criteria for ARVC include the presence of RV akinesia, dyskinesia, or aneurysms, together with an assessment of RVOT diameter and RV-fractional area change. Emerging echocardiographic parameters in the evaluation of patients with suspected or established ARVC include the measurement of tricuspid annular plane systolic excursion, RV basal diameter, global longitudinal strain (RV and LV), mechanical dispersion (RV and LV), and the use of 3D echocardiography.(77,78) However, prospective studies are needed before these assessments are recommended for routine use.

The 2010 Task Force Criteria for ARVC included cardiac MRI parameters for RV global and regional dysfunction and RV volume.(10) The major criterion requires a regional RV wall motion abnormality and either increased RV end-diastolic volume (≥110 mL/m^2 in men; ≥100 mL/m^2 in women) or depressed RV ejection fraction ≤40% (sensitivity: men 76%, women 68%; specificity: men 90%, women 98%). The CMR minor criterion also requires regional RV wall motion abnormality with lesser degrees of RV enlargement (≥100 mL/m^2 in men; ≥90 mL/m^2 in women).(10) The Task Force Criteria did not include CMR measures of RV myocardial fat or late gadolinium enhancement (LGE); however, these were not considered reliable measurements at the time the Task Force Criteria were developed (2010).

The 2010 Task Force Criteria for ARVC do not define diagnostic criteria for LV involvement. If present, LGE is typically found in a subepicardial or mid-wall distribution confined to the left ventricle. LV dominant disease may be underdiagnosed and attributed to other disorders.(78) The potential of CMR to diagnose and risk stratify patients with ACM remains to be fully exploited. LV LGE has been identified as the sole imaging abnormality in patients with desmoplakin disease who have arrhythmia of LV origin and a normal ECG.(31) In general, ECG abnormalities and arrhythmia are considered the earliest manifestations(54,79); however, Sen-Chowdhry et al have also demonstrated that CMR may be sensitive to detecting early changes in ARVC. The role of CMR in the early diagnosis of ACM of nondesmosomal origin, for other genetic and acquired causes, warrants evaluation.(30,80) CMR expertise will be particularly important in

the early diagnosis in the absence of ECG or other imaging abnormalities, given the risk that epicardial fat may be misinterpreted as delayed enhancement.

LV structural and functional abnormalities will relate to particular genetic abnormalities and diseasestage. Current genotype-phenotype relations are based on small data sets but suggest that ACM with clinically significant LV arrhythmias (eg, ALVC) may occur with "normal" to severely impaired LV function. Experience is greatest with lamin A/C disease, in which phenotypes include Emery-Dreifuss muscular dystrophy, generalized lipodystrophy, DCM with heart failure, progressive conduction disease with late-onset DCM, and ALVC with or without significant LV impairment. ALVC caused by *desmoplakin* variants can also be present with absent to severe LV dysfunction and may present with sudden death.(81) Preliminary experience indicates that LGE on CMR can be present in the absence of LV dysfunction and may provide an early diagnostic feature when LV arrhythmia appears to have occurred in isolation.(31)

3.6 Electrophysiology Testing

Electrophysiology testing in ACM is often unnecessary for the diagnostic evaluation of patients with suspected ARVC or ALVC.(12) Multicenter studies of patients with ARVC who received an implantable cardioverter defibrillator (ICD) have demonstrated the low predictive accuracy of electrophysiologic testing in identifying those at risk of SCD and/or life-threatening arrhythmia.(82,83) The reported incidence of "life-saving" ICD discharges for treatment of fast VT/ventricular fibrillation (VF) was not significantly different between those who were and those were not inducible. Corrado et al studied 106 patients with ARVC who received an ICD as primary prevention. The positive and negative predictive value for VT/VF inducibility was 35% and 70%, respectively.(82) Electrophysiological testing, however, may be beneficial in patients with refractory ventricular arrhythmias for ablation consideration and differentiation from RV outflow tract tachycardia. In this setting, electrophysiological testing with high-dose isoproterenol may help differentiate patients with idiopathic VT or ventricular premature beats from those with ARVC.(84)

3.7 Endomyocardial Biopsy

Biopsy can be particularly useful in identifying systemic or inflammatory conditions that cause ACM (eg, sarcoidosis, myocarditis). However, Endomyocardial biopsy (one of the Task Force Criteria for the diagnosis of ARVC) is invasive, lacks sensitivity and specificity, has low diagnostic

yield, and, therefore, is now rarely performed in the initial diagnosis of ARVC. The characteristic histological feature is the presence of transmural fibrofatty replacement of the RV myocardium, with major and minor criteria differentiated by degree of replacement (<60% vs 60%–75% myocytes by morphometric analysis).(10) Diagnosis by biopsy is limited due to false negatives secondary to patchy involvement and sampling error.(85,86) Electroanatomical voltage mapping may improve the yield of endomyocardial biopsy by identifying areas of low voltage.(87) Endomyocardial biopsy is associated with the risk of perforation, which is increased with RV free wall biopsy.(85,88) Septal biopsy is generally not helpful because it is typically the least affected area of the myocardium in ARVC.(86) Novel immunohistochemical analysis in ARVC patients with desmosomal variants demonstrated altered plakoglobin and connexin43 signal as a marker of disease expression(79,89-91); however, this has not proven to be of diagnostic utility. Sarcoidosis, for which treatment may include steroids, is important in the differential diagnosis of ARVC, but similar limitations with regard to sampling error and risk are present. Myocardial tissue obtained from postmortem and explanted hearts will have the value but not the limitations of endomyocardial biopsy and should be sought and examined whenever feasible.

3.8 Genetic Testing

General concepts on the role of genetic testing in the diagnosis and management of ARVC and other ACMs is outlined below, with recommendation flow diagrams shown in Figure 13 and Figure 14.

3.8.1 Genetic Testing Methods

Several methods are available to identify the genetic basis of an ACM. Single genes are usually analyzed by Sanger sequencing, which has been proven to be a reliable technique to identify variants underlying genetic disease and has been the gold standard for decades. With increasing numbers of genes identified as underlying a specific cardiac disorder (genetic heterogeneity) and the fact that more than one gene and/or variant (digenic inheritance or polygenic inheritance) can contribute to the disease phenotype,(75,92) next-generation sequencing (NGS)-based methods enable the parallel sequencing of several targeted genes (a panel, e.g, cardiomyopathy-panel) at the same time and at relatively low cost.(93) In addition to these targeted NGS panels, sequencing of all protein coding genes (exome) of the human genome

(whole exome sequencing, WES) or even all DNA nucleotides (whole genome sequencing, WGS) can be performed.

3.8.2 Variant and Gene Interpretation

DNA sequences normally vary in the general population when comparing different individuals. However, even when they reside in bona fide ACM-susceptibility genes, not every DNA variant contributes to the disease.(94) The major challenge is to correctly assign potential pathogenicity to these DNA variants. The American College of Medical Genetics and Genomics (ACMG) has published guidelines for interpreting genetic variants and proposed a classification based on the likelihood that a variant is related to disease (Table 2): pathogenic (class 5), likely pathogenic (class 4), uncertain significance (class 3), likely benign (class 2), or benign (class 1), in which a "likely pathogenic" and "likely benign" variant are used to mean greater than 90% certainty of a variant either being disease-causing or benign, respectively.(95)

Table 2. Classification of likelihood of pathogenicity of a variant. Adapted from Plon et al(96)

Classification of variant	Description	Likelihood of Being Pathogenic
Class 5	Pathogenic	>95%
Class 4	Likely pathogenic	>90%
Class 3	Variant of unknown significance	10-90%
Class 2	Likely benign	<10%
Class 1	Benign	<5%

The importance of correctly interpreting an identified variant's pathogenicity is now considered the most critical step in genetic testing, especially considering that there appears to be substantial interreviewer disagreement over variant interpretation.(97-100) Ethnicity information is essential for interpreting the data.(101) Within the ACMs, examples of incorrect classification of variants in major ARVC-related genes have been published.(102-106) Besides variant adjudication and the vexing variant of uncertain significance (VUS), many alleged and published ACM-susceptibility genes are being re-analyzed as to the strength of their disease-gene association and, over time, several published ACM-susceptibility genes may be demoted to

genes of uncertain significance (GUS). Accordingly, when evaluating patients suspected of an ACM, it is critical that the genetic tests conducted as part of the evaluation and the interpretation of the genetic test results be conducted by comprehensive teams with expertise in these disorders.(107)

Several genes have been implicated in ACM, with varying evidence strength (Table 3). The ClinGen Cardiovascular Clinical Domain Working Group for cardiovascular disorders is curating genes in relation to specific disorders.(108) One of the first efforts in adapting the ACMG 2015 guidelines for variant interpretation in genes related to cardiogenetic disease has recently been published, and this process is also underway for ACM.(109)

Depending on the reason for using the results of a genetic test, a certain amount of evidence for pathogenicity is necessary; for prenatal diagnostics or a pre-implantation genetic diagnosis, the evidence for pathogenicity must be strong, and only class 5 variants are used. For genetic cascade screening in family members, only class 4 and 5 variants are used; family members negative for the family's class 5 variant are dismissed from regular cardiologic follow-up, whereas those relatives who test negative for a given family's class 4 variant remain in the cardiogenetic clinics, albeit for longer follow-up intervals. The frequency and duration of follow-up for family members who are negative for a class 4 variant should be individualized at the discretion of the clinical team. Class 3 variants (ie, a VUS) should be deemed "nonactionable". Given both incomplete penetrance and age-dependent penetrance, clinically unaffected family members should not be tested to determine their status for a class 3 variant found in the family unless additional evidence (such as various functional validation assays and/or demonstration of co-segregation among clinically affected family members) has been obtained that would prompt a variant promotion from an ambiguous class 3 variant (VUS) to a clinically actionable class 4 or class 5 variant.

3.8.3 Which Test to Use

With the availability of NGS, the number of genes that can be studied in a single patient rapidly increases. However, the value of including a greater number of genes in a panel should be weighed against the drawback of adding genes that have insufficient evidence (or none) of being related to the patient's disease or that account for only a small percentage of the genotyped patients and are therefore more prone to errors in attributing the pathogenic role of the identified variants.

Therefore, a list of core genes can focus on those with sufficient evidence to be disease-related. The ClinGen working group for cardiovascular disorders is responsible for reviewing clinical, genetic, and experimental data to establish the strength of evidence level of evidence supporting gene-disease associations in heart disease. Gene curation for HCM was recently completed, and curation for ARVC and DCM is underway.(110,111) Until the official ClinGen-approved results of these gene curation efforts are available, we anticipate that the genes listed in Table 3 will likely be retained as ACM-susceptibility genes with sufficient evidence to merit their disease–gene association and will be useful in clinical practice. these recognized genes should therefore be prioritized for patients and families with a clinical diagnosis of ACM or its subforms. If other genes are included in the analysis, identifying a pathogenic or likely pathogenic variant in one of the non-ACM related genes should not automatically or reflexively be considered an explanation for the patient's ACM phenotype. In other words, a pathogenic or likely pathogenic variant in *KCNH2* (a gene in which P/LP variants cause abnormalities in the QTc without structural heart disease) does not carry the same intrinsic probability of pathogenicity for ACM as a *plakophilin-2(PKP2)* variant that has been graded as a pathogenic or likely pathogenic variant.

A recent viewpoint paper by the European Society of Cardiology working group on myocardial and pericardial diseases emphasized that, in a diagnostic setting, only recognized genes associated with the condition should be investigated in patients who meet the diagnostic criteria of a specific cardiovascular condition. WES and WGS should be used for genetic diagnosis only if filtered against recognized disease-causing genes. The coverage should enable the identification of all exonic variants in these genes.(107)

Table 3. Minimum set of genes to be prioritized in ACM. These genes have multiple lines of evidence indicating involvement in ACM and its subtypes (ALVC, ARVC). OR/EF and Signal:Background data are largely derived from cohorts with western European ancestry, and other ethnicities can be different. ACM=arrhythmogenic cardiomyopathy; AV=atrioventricular; BV=biventricular; Ca=calcium handling; CD=conduction delay; CHD=congenital heart disease; CPVT=catecholaminergic polymorphic ventricular tachycardia; *DES=desmin*; Desm=desmosomal; *DSC2=desmocollin-2*; *DSG2=desmoglein-2*; EF=etiological fraction; IF=intermediate filament; LD=left dominant; NA=data not available; NE=nuclear envelope; ns=not significant; NT=nontruncating variants; OR=odds ratio; RD=right dominant; SND=sinus node dysfunction; T=truncating variants; *=genes with significant excess in cases over *ExAc* reference samples.(100) Other genes that have been identified in ACM with insufficient or conflicting evidence are**:** *ABCC9,*(112) *TGFB3,*(113) *TTN*,(114) *CTNNA3,*(115) sarcomeric genes (*MYH7, MYBPC3*),(116,117) *SCN3B*,(117) *CDH2,*(118,119) *TJP1.*(120)

Gene	Protein Type	Predominant Type of Mutation	OR/EF (100)	Signal: Background (94)	Remarks	References
BAG3	Chaperone	Truncating and missense	NA	NA	Also causes myofibrillar myopathy	(121)
DES	IF	Truncating and missense	NA	NA	Also causes myofibrillar myopathy	(122)
DSC2	Desm	Truncating and missense	NT 2.15 (EF 0.53); T21.5* (EF 0.95)	ns ns	Rare	(26)
DSG2	Desm	Truncating and missense	NT 2.83* (EF 0.65) T 19.8* (EF 0.95)	2:1* (NT/T)	Rarely recessive	(123)
DSP	Desm	Truncating and missense	NT 2.1* (EF 0.52) T 89.9* (EF 0.99)	ns ns	Recessive: Carvajal syndrome	(23,124)
FLNC	Actin crosslink	Truncating and missense	NA	NA	Also causes myofibrillar myopathy	(34)
JUP	Desm	Missense	NT 7.8* (EF 0.87) T 28.1 (EF)		Recessive: Naxos syndrome	(22,125)
LDB3	Z-band	Missense	NA	NA	Cypher/ ZASP	(126)
LMNA	NE	Truncating and missense	NA	NA	AV block; CD	(127)
NKX2-5	Homeobox	Truncating and missense	NA	NA	AV block, CD, CHD	(128)

PKP2	Desm	Truncating	NT:1.3 (EF 0.23) T:484.7* (EF 1.0)	10:1* 42:1*	Large deletions 1-2%	(24)
PLN	Ca	Missense, nonsense, and deletion	NA	NA	Predominantly R14del	(33,129)
RBM20	Splice factor	Missense	NA	NA	Mostly in exon 9	(130)
SCN5A	Sodium channel	Mostly missense	NA	NA	Brugada, SND, CD	(131)
TMEM 43	NE	Missense	NT 0.76- T 13-	ns	p.S358L disease-causing; also called LUMA	(132)

3.8.4 Advantages and Disadvantages of Various Methods

The various techniques that can be used for genetic testing each have their own advantages and disadvantages, as summarized in Table 4. Coverage of the genomic regions of interest, the possibility of identifying large deletions/duplications, flexibility, and costs are important factors to consider when ordering a genetic test.

Sanger sequencing is a reliable method with good coverage of the nucleotides that need to be studied, particularly for evaluating a single or a small number of genes. Sanger sequencing is also appropriate for cascade testing in at-risk family members, clinical confirmation of research genetic results, and cosegregation studies. However, large deletions and duplications of genes can be missed when using Sanger sequencing. It is well known that larger deletions and/or duplications (eg, in *PKP2*) are a known cause of ACM(68,133,134) and can be identified in a small percentage of cases.

Targeted NGS panels have the advantage that they are well validated, and it is well known which parts are insufficiently covered. Additional Sanger sequencing experiments are frequently used to evaluate the insufficiently covered regions.(93) Bioinformatic tools must be added to the bioinformatics pipeline to identify deletions and/or duplications in the genes of interest in targeted panel screening, a relatively inexpensive, fast, and reliable method to study larger series of genes.

The results of exome sequencing, a relatively fast test, can be filtered against the set of core genes rather than evaluating all 20,000+ human genes. This reduces the chance of incidental

findings. The major advantage of exome sequencing is that novel or additional genes can be easily added by "opening" the data whenever new disease genes are established. On the downside, the quality and/or coverage of some parts of the "core genes" may be insufficient, and larger deletions and/or duplications can easily be missed.

Table 4. Different methods for screening genes. CNVs=copy number variations; IE=inefficient (expensive for large amounts of sequencing but inexpensive for a small amount); NGS=next generation sequencing; WES=whole exome sequencing; WGS=whole genome sequencing; ++=very high; +=high; +/-=intermediate; -: low; --: very low.

	Target	coverage	CNVs	Flexibility	costs
Sanger sequencing	Single gene(s)	++	--	-	IE
Targeted NGS panel	Panel of genes of interest	+	+	-	+/-
WES filtered against genes of interest	Set of genes of interest	+/-	+/-	+	+
WES	All genes	+/-	+/-	+	+
WGS	All genes +intronic sequences	+	+	+	++

3.8.5 Who to study

COR	LOE	Recommendations	References
I	C-EO	For individuals and decedents with either a clinical or necropsy diagnosis of ACM, genetic testing of the established ACM-susceptibility genes is recommended.	
I	C-EO	For genetic testing of the established ACM-susceptibility genes, comprehensive analysis of all established genes with full coverage is recommended	

A genetic test is generally performed in an index patient with either a clinical diagnosis that fulfills the clinical criteria for the disease in question or when there is at least a reasonable index of suspicion for that specific disorder. Both the selected disease gene panel and the subsequent genetic test interpretation should be strongly influenced by the veracity of the phenotype. The genetic testing of patients with nonspecific syncope or T wave inversions confined to only precordial lead V1, for example, should be strongly discouraged.(135) When interpreting a genetic test, the available evidence that a specific gene is related to ACM should be taken into account. The test used should be of sufficient quality to identify variants in these genes. This may entail additional tests to cover all exons and additional bioinformatic and laboratory tests to identify deletions and duplications.

For individuals who have died suddenly with a postmortem (likely) diagnosis of ACM or one of its subforms, postmortem genetic testing should again include those disease genes implicated in the necropsy diagnosis. Various sources to isolate DNA can be used, such as blood, frozen tissue, fibroblasts from a skin biopsy, and even formalin-fixed paraffin-embedded tissue.(136,137)

ACM-associated genes can also be evaluated in autopsy-negative SCD cases because ventricular arrhythmias leading to SCD may precede structural abnormalities.(138)

Table 3 lists the minimum set of genes to be evaluated.

3.8.6 The Role of Genetic Testing in Arrhythmogenic Cardiomyopathies

A positive genetic test result (ie, likely pathogenic, class 4 or pathogenic variant, class 5) can (1) genetically confirm the clinical diagnosis and provide disease–gene-specific risk stratification and tailoring of therapies(139) and (2) enable variant-specific cascade genetic testing of appropriate family members and relatives (see Section Family Screening), including the potential for prenatal or preimplantation genetic diagnostics (a topic beyond the scope of this article).

In the current Task Force Criteria for ARVC,(10) the “Identification of a pathogenic mutation categorized as associated or probably associated with ARVC in the patient under evaluation” is weighted as a **major** criterion in the “family history” section. A pathogenic mutation (now classified as either a class 4 or class 5 variant per ACMG nomenclature) is defined as “a DNA alteration associated with ARVC that alters or is expected to alter the encoded protein, is

unobserved or rare in a large non-ARVC control population, and either alters or is predicted to alter the structure or function of the protein or has demonstrated linkage to the disease phenotype in a conclusive pedigree". Since A positive genetic test result is regarded as a major criterion, it will contribute up to 50% to the diagnosis of ARVC, thus highlighting the importance of an experienced genetic team. Nevertheless, there is the question of whether to put this much weight on a genetic result for which the true characteristics such as penetrance are generally not well known.

3.8.7 The Use of a Genetic Test in Risk Stratification and Management

Whether the result of a genetic test can be used for risk stratification or management depends on the known relationship between genotype and phenotype. In general, there is limited evidence for a clinically actionable relationship between genotype and phenotype, with a few exceptions presented in the following subsections.

3.8.7.1 Left Ventricular Dysfunction

LV dysfunction is most often present in ACM patients with pathogenic or likely pathogenic variants in LMNA, BAG3, or one of the founder variants in the *PLN* and *TMEM43* genes, followed by variants in *DSP*, *DSG2/DSC2* and the lowest frequency in *PKP2/JUP*. This holds true for both index patients and family members.(140,141)

3.8.7.2 Multiple Variants

Approximately 3%–6% of patients have more than 1 pathogenic or likely pathogenic variant contributing to the disease phenotype. Patients with multiple pathogenic variant-mediated ACM have more severe disease, as reflected by an earlier age at disease onset(92) and the presence of VTs (<20 years vs 35 years for patients with a single ACM-causative variant),(68) a higher lifetime risk of arrhythmia(142) or SCD(143), and earlier progression to cardiomyopathy.(141,144,145)

3.8.7.3 Specific Variants and Genes

3.8.7.3.1 Desmosomal Genes

Disease expression reaching diagnostic criteria is most common between 20 and 50 years of age (40%; 95% CI, 34%–46%),(146) although in one series, 9 of 40 pediatric desmosomal gene-positive patients had the disease at a mean age of 17.8 ± 5.1 years.(147) LGE identified by

cardiac MRI, most frequently seen in the LV myocardium, was the first evidence of disease expression in a small subset of individuals.(75) In a comprehensive evaluation of 274 family members, the incidence of a new diagnosis (as per 2010 Task Force Criteria) in those aged 10–20 years was 0.5 per 100 person-years, and the odds ratio of a diagnosis in those aged <18 years in the multivariate analysis was 0.37 (0.14–0.93), with no diagnosis reached under the age of 14 years. Likewise, a new diagnosis in relatives older than 60 years is less common.(146) The cumulative prevalence by decade is shown in Figure 9 based on data from Quarta et al.(147)

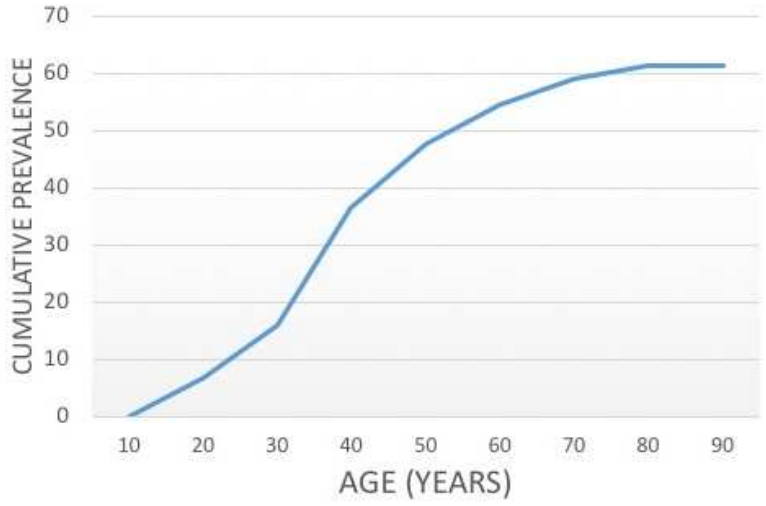


Figure 9. Cumulative prevalence of disease expression in family members at risk of ARVC.(147)

Overall, relatives have less severe disease compared with probands, are more commonly asymptomatic, and show disease onset at an older age.(145) Arrhythmic events in family members appear to occur only in the presence of manifest electrocardiographic and structural changes.(146,148) Similar enhanced disease activity is observed in pediatric probands compared with their age-matched relatives.(75)

3.8.7.3.2 Lamin A/C (LMNA)

The cardiac phenotype for *LMNA*-mediated ACM is characterized by atrial fibrillation, cardiac conduction disease, which may precede the development of ventricular arrhythmias and cardiomyopathy by decades.(149,150) *LMNA* variants have also been identified in patients diagnosed with ARVC(151-153); or more biventricular and left-dominant forms of the

disease.(127,154) Risk stratification has been reported from Asian and European populations (155,156) In the European study, nonsustained ventricular tachycardia (NSVT), LVEF<45% at first clinical contact, male sex, and non-missense variants have been reported to be risk factors for malignant ventricular arrhythmias.(156) Patients with a *LMNA* variant who are in need of a pacemaker often receive an ICD which is effective in treating possibly lethal tachyarrhythmias.(157)

3.8.7.3.3 Desmoplakin (DSP)

Pathogenic variants in *DSP*-encoded desmoplakin are associated with a spectrum of disorders, including cardio-cutaneous syndromes. For patients with likely pathogenic (class 4) or pathogenic (class 5) variants in *DSP* over 50% of index-patients and 17% of family members have an arrhythmic phenotype with LV dysfunction (Table 2).(141) In addition to biventricular forms, left dominant forms are also present and extensive fibrotic patterns can be identified by MRI (see Section 5.4 Left Ventricular Noncompaction).(140,158)

3.8.7.3.4 Transmembrane Protein 43 (TMEM43)

The p.S358L mutation in transmembrane protein 43 (*TMEM43*) is a specific founder variant that has been identified in a large number of patients diagnosed with ARVC from Europe and Canada (Newfoundland).(132,159) Its clinical phenotype is characterized by poor R wave progression in precordial leads and LV enlargement in 43% of affected individuals, with 11% meeting the criteria for DCM.(160) A study involving nearly 150 p.S358L-*TMEM43*-positive individuals concluded that survival was greater for those treated with an ICD than for those with conventional, non-ICD care.(160)

3.8.7.3.5 Phospholamban (PLN)

The pathogenic p.R14del-*PLN* variant has been identified in 1% of patients with ARVC in the United States and 12% of Dutch patients with ARVC(33), as well as in patients from several other countries (Spain, Germany, Greece, Canada, Norway). Patients with this variant frequently have low-voltage ECGs and are considered to be at high risk for malignant ventricular arrhythmias and end-stage heart failure, with LVEF <45% and sustained VT or NSVT as independent risk factors (see Section 5.3.4).(161)

3.8.8 Limitations of genetic testing

COR	LOE	Recommendations	References
IIa	C-EO	The interpretation of a cardiac genetic test by a team of providers with expertise in genetics and cardiology can be useful.	

Performing a genetic test on an index patient or relative has several aspects that must be considered and thus require a comprehensive, expert team. There are specific test-related "technical" aspects that result in some variants not being detected by certain tests (see Section 3.8.4). The interpretation of a genetic test requires an accurate interpretation of variants. For example, class 1, 2, and 3 variants are not considered as actionable. The interpretation is also influenced by the pretest probability, which depends greatly on the precise clinical characterization of the phenotype. Additionally, the identification of a genetic defect does not necessarily predict the disease severity in that specific individual. When using a panel with more genes that underlay other phenotypes, incidental findings may be identified; such as, likely pathogenic or pathogenic variants (class 4 and 5) that could lead to a different phenotype than the one that motivated the referral.

Genetic testing can cause a mixture of positive and negative emotions for the patient. Genetic counselors can help patients and their families navigate these feelings and learn to live with this inherited condition. Genetic counselors can explain the implications of identified genetic variants in ways that alleviate anger, anxiety, fear, and guilt that are likely to occur in patients and their families.

This expert team should therefore consist, at minimum, of cardiologists, clinical and molecular geneticists, genetic counselors, and pathologists, or individuals with expertise that encompass these subspecialties.

The ACMG has issued an updated list of over 50 actionable genes.(162) Laboratories performing WES or WGS (generally for diagnostic odyssey cases) should report the presence of pathogenic or likely pathogenic variants residing in these genes, unless the individual who is being tested has chosen not to receive these results. This list includes 5 of the established ARVC-susceptibility genes. For these incidental findings, however, the frequency of related clinical phenotypes in unselected patient populations is generally not well established. When variants in a known ARVC-susceptibility gene are identified in the context of a nonphenotype-driven incidental

finding, the likelihood that this variant (even if graded as a class 4 or 5) portends the presence of ARVC or the risk of developing ARVC in the future is considered low, as was recently established for arrhythmia and ARVC-related genes.(98,163)

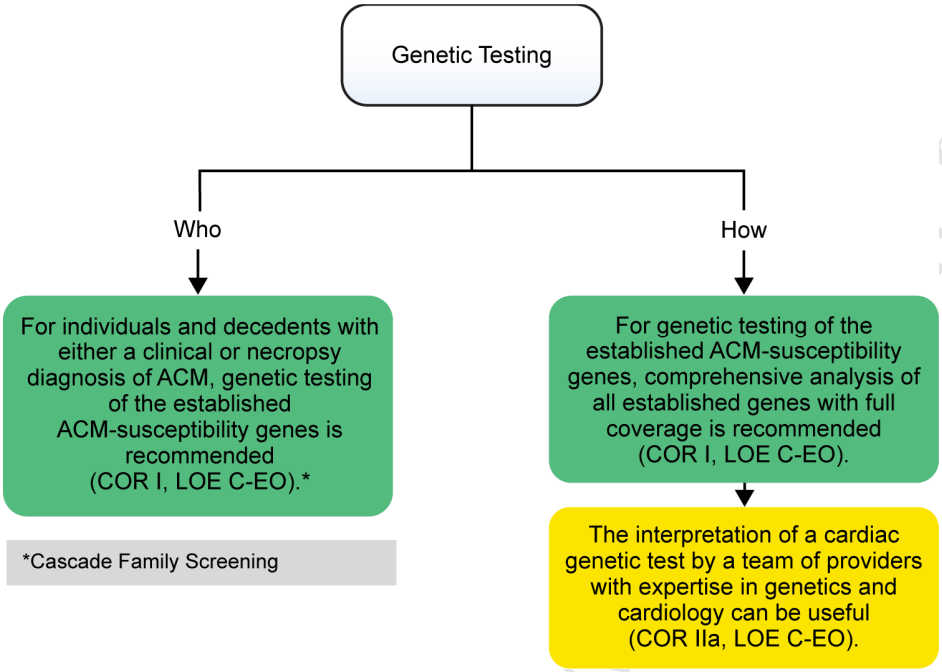


Figure 10. Genetic testing recommendations. *=Cascade family screening: see Section 3.9. ACM= arrhythmogenic cardiomyopathy; COR=Class of Recommendation; LOE=Level of Evidence. Colors correspond to COR in Figure 1.

3.9 Cascade Family Screening

See Evidence Table: Cascade Family Screening. Flow chart of recommendations is shown in Figure 11.

3.9.1 Cascade Family Screening: Screening Recommendations in Children and Adults

Clinical cascade testing refers to the cardiovascular and genetic evaluation of first-degree family members of an individual (proband) with a confirmed diagnosis of ACM and is ideally performed within the confines of a multidisciplinary cardiovascular genetics program, familiar with the clinical and genetic complexities of the condition.(164) The underlying etiology of ACM in many cases is due to alterations in cardiac genes that encode proteins critical to normal heart development and/or function. For the most part, these are inherited as an autosomal-dominant trait, such that first-degree family members have a 50% *a priori* risk of developing ACM, although the penetrance and disease severity are typically less in family members compared

with probands.(145) Detailed clinical and genetic familial evaluation, both at the time of diagnosis and during follow-up, will help determine the inheritance patterns and likelihood of consanguinity.

Desmosomal variants are relatively common in control populations and may erroneously be considered disease-causing,(94) although certain variants have a well-recognized association with the condition, and targeted genetic testing can be used in isolation within specific families.

3.9.1.1 Family history

COR*	LOE	Recommendations	References
I	C-EO	It is recommended that a genetic counselor or appropriately experienced clinician obtain a comprehensive 3-generation family history.	
A detailed ≥ 3-generation family history collected from the proband at their initial consultation is vital and should be obtained by a genetic counselor or an appropriately experienced clinician.(165-168) The family history can be used to determine the existence of familial disease, provide important data regarding the full phenotypic spectrum within the family, and identify relatives who should be informed of the need for cardiac evaluation.			

3.9.1.2 Cardiac Evaluation

The yield of cardiac screening is highly varied due to age-related and typically incomplete penetrance, and the disease spectrum can be diverse, even within families harboring the same variant, incorporating right-sided, left dominant, and biventricular phenotypes. Family members may display a relatively mild or incomplete phenotype, including subtle electrocardiographic or structural abnormalities.

3.9.1.3 Age-Related Penetrance of Disease in At-Risk Relatives

COR*	LOE	Recommendations	References
I	B-NR	It is recommended that first-degree relatives undergo clinical evaluation every 1-3 years starting at 10-12 years of age.	(34,75,146,160,161, 169,170)

ACM variants can display incomplete penetrance and varied expression. In ARVC there is age-related penetrance with onset typically observed in the third and fourth decade of life, although this may vary with the underlying etiology and specific familial characteristics. Disease expression is, however, recognized in adolescents, although it is extremely rare under the age of 10 and is almost exclusively seen in probands.(75,145,171) At-risk relatives who undergo clinical evaluation may be clinically affected, have borderline disease (incomplete penetrance), or be clinically unaffected. Serial evaluation can define ongoing disease expression and risk stratification.(50,147) In a study of families with ARVC, the highest probability of a diagnosis of ARVC occurred between 20–50 years of age (40%; 95% CI, 34%–46%).(146)

COR*	LOE	Recommendations	References
I	B-NR	Cardiovascular evaluation should include 12-lead ECG, ambulatory ECG, and cardiac imaging.	(21,75,145-147,172-174)

Evaluation of all at-risk family members should include a 12-lead ECG, 24-hour Holter monitoring, and cardiac imaging. The exact imaging modality (echocardiogram, cardiac MRI, or CT) can vary depending on availability and institutional expertise. A study of relatives harboring a *PKP2* causal variant identified in the proband showed that approximately one-third had a diagnosis of ARVC, one-third had borderline disease, and one-third were unaffected,(172) although other studies have shown a much lower diagnostic rate among family members.(173) In relatives who demonstrate disease features, electrocardiographic changes typically occur earlier and more commonly than structural changes,(174) although subtle structural abnormalities can be identified by detailed echocardiographic analysis.(77,175) LGE on cardiac MRI, most frequently observed in the LV myocardium, was the first evidence of disease expression in a small subset.(75)

3.9.1.4 Cascade Cardiac Investigations

COR*	LOE	Recommendations	References

IIb	C-LD	Exercise stress testing (arrhythmia provocation) may be considered as a useful adjunct to cardiovascular evaluation.	(148)
In addition, exercise stress testing may expose a latent phenotype by initiating ventricular ectopy or arrhythmia.(148) Symptoms such as syncope or palpitations should initiate an urgent evaluation.			

3.9.1.5 Cascade Genetic Testing

When a likely pathogenic or pathogenic genetic variant has been identified in the proband, cascade genetic testing can be offered to first-degree at-risk relatives. Cascade genetic testing should only be offered in the context of comprehensive pretest genetic counseling, with the goal is to discuss the process of genetic testing; the implications of the results for patients and their family members; social, lifestyle, and insurance implications; and an examination of patients' feelings about either a positive or negative result.(166,176) Inappropriate use of genetic testing in a family has the potential to introduce unnecessary worry and fear, as well as potential harms related to the misinterpretation of genetic variants.(166,176) Cascade genetic testing is therefore only offered to family members where a likely pathogenic or pathogenic variant in a known disease-associated gene is identified in the proband and can be interpreted with an appropriate level of expertise. Consideration must also be given to the family members'' psychosocial wellbeing.

Efforts to ensure ongoing reclassification of variants are critically important for cascade genetic testing and families benefit from being managed in a specialized multidisciplinary cardiac genetic service. Ideally, systematic processes or a combined approach of relying on new information from the testing laboratories and review of family variants triggered by a family member returning for routine follow-up should be in place.

COR*	**LOE**	**Recommendations**	**References**

IIb	C-EO	In families with a variant classified as pathogenic, it may be reasonable for asymptomatic members of a family who do not have the familial variant and have a normal cardiovascular evaluation to be released from regular screening and educated to return if disease symptoms occur.	
At present, the key role of genetic testing for many ACM conditions is to identify asymptomatic carriers who can be targeted for closer surveillance or gene-negative relatives who are unlikely to develop disease and can be released from future screening.(169) Comprehensive cardiovascular and genetic investigation will also help confirm variant status within the wider family. Family members who are comprehensively evaluated and who do not carry the pathogenic variant may be released from further regular evaluation, although they should be educated regarding specific symptoms and advised to seek further evaluation should these occur.			

3.9.1.6 Cascade Genetic Testing in Minors

Cascade testing for familial variants in children remains controversial, given the complex medical, legal, and psychological issues involved. Testing is typically deferred until an age when clinical features are more likely, although this can be affected by the clinical disease spectrum and segregation of the variant in other family members, coupled with the specific preferences of the child and family. Genetic testing should always be guided by the child's best interest and performed by a multidisciplinary team including specialist cardiologists, geneticists, genetic counselors and psychologists with expertise in genetic counseling, variant interpretation and disease management, when feasible.

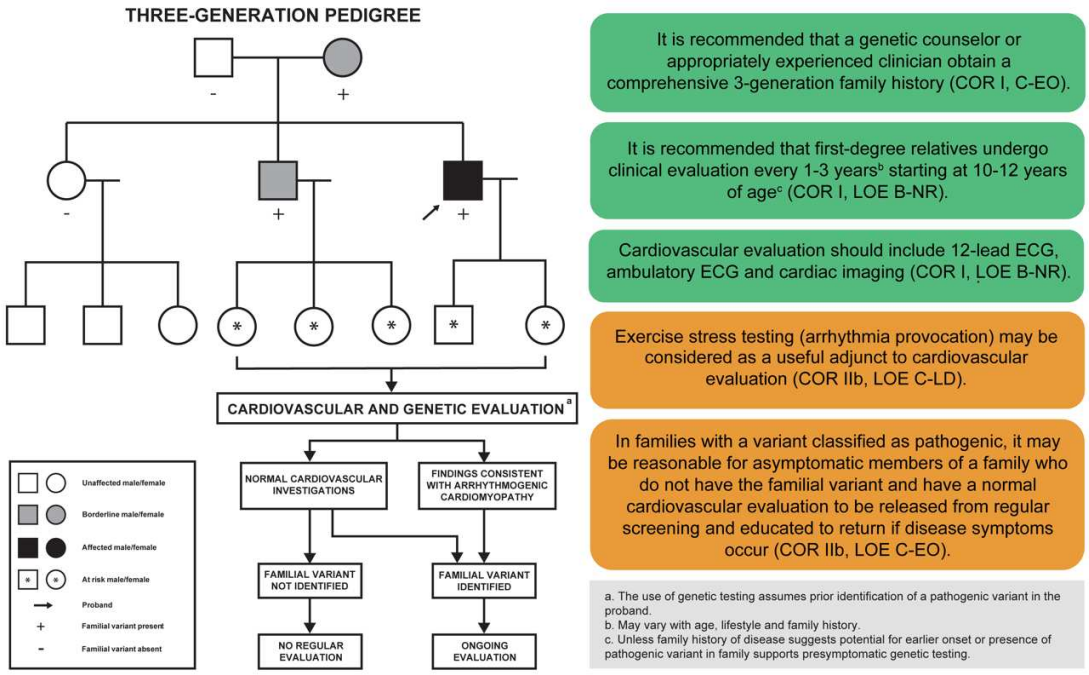


Figure 11. Summary of family screening recommendations. Colors correspond to Class of Recommendation in Figure 1. COR=Class of Recommendation; ECG=electrocardiogram; LOE=Level of Evidence. Colors correspond to COR in Figure 1.

3.10 Risk Stratification and ICD Decisions

See Evidence Table: Risk Stratification and ICD Decisions. The recommendation flow diagram is shown in Figure 12.

SCD most feared consequence of ACM. In a series of SCD occurrences in young individuals, ARVC accounts for up to 20% of the cases, particularly in certain genetic ethnic populations. There are fewer data on the contribution of other ACMs to SCD, likely a result of the difficulty of diagnosing these diseases postmortem. Prevention of SCD is possible with ICDs; identifying patients at risk of SCD is necessary to target those who should receive ICDs.

COR	LOE	Recommendations	References

I	C-EO	The decision to implant an ICD in an individual with ACM should be a shared decision between the patient and the physician, taking into account the risks and benefits of the ICD over the potential longevity of the patient.	
A shared decision-making process is essential to clarify the anticipated benefits of an ICD to for each individual patient. Potential options for therapy and the evidence supporting them are discussed to enable patients to make an informed decision.			

Risk stratification is limited by the available data, nearly all of which are retrospective in nature and obtained from patients referred to tertiary care centers. Also, some of the larger, more recent registry data almost certainly contain patients which were previously reported in prior publications from the same center. Thus, the largest, most recent registries are the most reliable in terms of risk assessment.

Most series include patients with ICDs; in fact, in some series an ICD is a requirement for entry into the registry. Appropriate therapies for VT, ventricular flutter (VFL), and VF are included as endpoints. ICD-treated arrhythmias are used as a surrogate for SCD, but there is abundant evidence that not all ICD-treated arrhythmias would have led to SCD. To make the SCD endpoint more specific and detailed, a number of studies have the separate endpoints of potentially life-threatening arrhythmias and all ventricular arrhythmias. In these studies, life-threatening arrhythmias are generally defined as SCD or hypotensive VT in patients without ICDs and ICD-treated VF or VFL ≥240 bpm in those with ICDs. All arrhythmias are generally defined as any sustained arrhythmia (>30 seconds) that spontaneously occurs and any ventricular arrhythmia treated by the ICD, including treatment with ATP or shock. Some registries include cardiovascular death, heart transplantation, and ventricular arrhythmias for a composite endpoint. An international collaboration of 18 centers from Europe and North America developed a risk model,(177) where male sex, relative youth, ECG, imaging features reflecting more extensive RV disease, and the severity of ventricular arrhythmia were the most accurate identifiers of the high-risk cohort studied. The model provides 1 to 5-year ventricular arrhythmia event-free survival rates for the predicted high-risk group and the potential to determine five-year risk in the individual patient.

COR	LOE	Recommendations	References
I	B-NR	In individuals with ACM who have suffered a cardiac arrest with VT or VF an ICD is recommended.	(83,178-182)
I	B-NR	In individuals with ACM who have sustained VT not hemodynamically tolerated, an ICD is recommended.	(83,178-180,182)
As with other diseases, previous sustained ventricular arrhythmia is undoubtedly the strongest predictor of recurrent ventricular arrhythmia. Cohort studies that included patients with ARVC and ventricular arrhythmic (VT or VF) events prior to enrollment have shown that these arrhythmic events are a strong predictor of future life-threatening ventricular arrhythmias; an ICD can therefore be a life-saving device.(83,178-180)			

COR	LOE	Recommendations	References
IIa	B-NR	In individuals with ACM and syncope suspected to be due to a ventricular arrhythmia, an ICD is reasonable.	(82,83,178-180,183-189)
Syncope is a common symptom in young individuals, and it is important to clarify that syncope is likely due to a ventricular arrhythmia. In cohort studies, syncope is an independent predictor of future ventricular arrhythmic events.(82,83,178-180,183,184) In the Pavia Registry, 73 of 301 patients followed for a mean of 5.8 years had a clinical outcome of SCD, aborted SCD, syncopal VT or electrical storm, or cardiovascular mortality,(183) with a history of syncope being an independent predictor (hazard ratio (HR): 4.38; *P*=.002). In the Hopkins Registry, 186 of 312 patients followed for 8.8±7.3 years had a clinical outcome of VT or VF with syncope as a univariate predictor (HR: 1.85; *P*=.021).			

COR	LOE	Recommendations	References
IIa	B-NR	In individuals with ARVC with hemodynamically tolerated sustained VT, an ICD is reasonable.	(178-180,183)

Hemodynamically tolerated VT has also been associated with adverse arrhythmic outcomes. In the Pavia registry, 73 of 301 patients followed for a mean of 5.8 years had a clinical outcome of SCD, aborted SCD, syncopal VT or electrical storm, or cardiovascular mortality(183). Hemodynamically tolerated monomorphic ventricular tachycardia was an independent predictor (HR: 2.19; *P*=.023). In the Hopkins registry, VT at presentation was a univariate predictor for VT (HR: 1.86; *P*<.001).

COR	LOE	Recommendations	References
IIa	B-NR	ICD implantation is reasonable for individuals with ARVC and three major, two major and two minor, or one major and 4 minor risk factors for ventricular arrhythmia.*	(179,180,183,190)
IIb	B-NR	ICD implantation may be reasonable for individuals with ARVC and two major, one major and two minor, or 4 minor risk factors for ventricular arrhythmia.*	(179,180,183,190)

*Major criteria: NSVT, inducibility to VT at EPS, LVEF≤49%. Minor criteria: male sex, >1000 premature ventricular contractions (PVCs)/24 hours, RV dysfunction (as per major criteria of the 2010 Task Force Criteria, see Figure 6), proband status, 2 or more desmosomal variants. If both NSVT and PVC criteria are present, then only NSVT can be used.

The variables associated with VT/VF in more than one cohort include younger age at presentation (significant in 4 series)(83,179,180,190) and male sex (significant in 2 series).(183,190) The variables associated with VT/VF in only one study include NSVT,(82) PVC frequency >1000/24 hours,(180) VT inducibility at EPS,(180) atrial fibrillation,(183) hemodynamically tolerated monomorphic VT,(183) participation in strenuous exercise,(183) and reduced LVEF.(83)

COR	LOE	Recommendations	References

I	B-R	In individuals with ACM with LVEF 35% or lower and NYHA class II-III symptoms and an expected meaningful survival of greater than 1 year, an ICD is recommended.	(182,185-188,191)
ACM may be secondary to a wide variety of genetic defects and acquired abnormalities. Some may have structural and functional abnormalities that overlap with DCM. Etiologies are more likely to present early in their clinical course with ventricular arrhythmias, particularly the inherited cardiomyopathies caused by pathogenic variants in PLN, LMNA, FLNC, TMEM43, RBM20, and DES. In large randomized controlled trials that enrolled patients with DCM, ICDs improved survival. Patients enrolled in these trials had New York Heart Association (NYHA) class II or III symptoms and were undergoing guideline-directed medical therapy for heart failure.			

COR	LOE	Recommendations	References
IIa	B-R	In individuals with ACM with LVEF 35% or lower and NYHA class I symptoms and an expected meaningful survival of greater than 1 year, an ICD is reasonable.	(187)
The Defibrillators in Non-Ischemic Cardiomyopathy Treatment Evaluation (DEFINITE) trial included patients with nonischemic DCM and NYHA I symptoms, comprising 99 of 458 patients who were randomized to an ICD vs medical therapy for the prevention of SCD.			

COR	LOE	Recommendations	References
I	B-NR	In individuals with ACM (other than ARVC) and hemodynamically tolerated VT, an ICD is recommended.	(156,161)
IIa	B-NR	In individuals with phospholamban cardiomyopathy and LVEF<45% or NSVT, an ICD is reasonable.	(161)
IIa	B-NR	In individuals with Lamin A/C ACM and two or more of the following: LVEF<45%, NSVT, male sex, an ICD is reasonable.	(156)

In a cohort of 403 patients from The Netherlands with the founder R14del variant in PLN, independent variables associated with malignant arrhythmias included LVEF <45%, sustained VT or NSVT.(161) Other variables were associated with malignant arrhythmias, but none of these remained significant after multivariate analysis. Although sustained VT was not studied in the Lamin A/C cohorts, a finding of NSVT on Holter monitoring was a significant predictor for spontaneous VT/VF in a cohort of 269 patients.(156)

In patients with Lamin A/C, several clinical variables are associated with the risk of spontaneous VT/VF or ICD-treated VT/VF. In a cohort of 269 patients from a European registry, NSVT on Holter monitoring, LVEF <45%, and male sex were associated with VT/VF, but only if a patient had 2 or more of these factors.(156) In an international registry of 122 patients, male sex, LVEF ≤50% at the first clinical contact, and nonmissense variants were independent predictors of arrhythmias.(32) In this study, the risk of arrhythmia increased exponentially as the number of these predictors increased. During the 7-year follow-up, the incidence of sustained VT/VF was 9% with 1 of these risk factors, increasing to 28% with 2, 47% with 3, and 69% with 4 risk factors.

COR	LOE	Recommendations	References
IIa	C-LD	In individuals with FLNC ACM and an LVEF<45%, an ICD is reasonable.	(34)

Variants in FLNC are associated with several skeletal and cardiac myopathies. Recognition of FLNC has recently been recognized as an ACM, resulting, in part, from the identification of truncation variants in 28 unrelated cardiomyopathy patients referred to a gene testing laboratory in Spain.(34) Familial evaluation led to the identification of 54 individuals with a FLNC variant. SCD and arrhythmias treated by an ICD were frequent. In the 12 patients with SCD, the mean LVEF was 39.6% ± 12%.

COR	LOE	Recommendations	References
IIa	C-LD	In individuals with Lamin A/C ACM and an indication for pacing, an ICD with pacing capabilities is reasonable.	(149,170,189)

In some cohort studies,(149,170,189) atrioventricular block was a univariate predictor for VT or VF, thereby justifying consideration of an ICD if pacing is needed

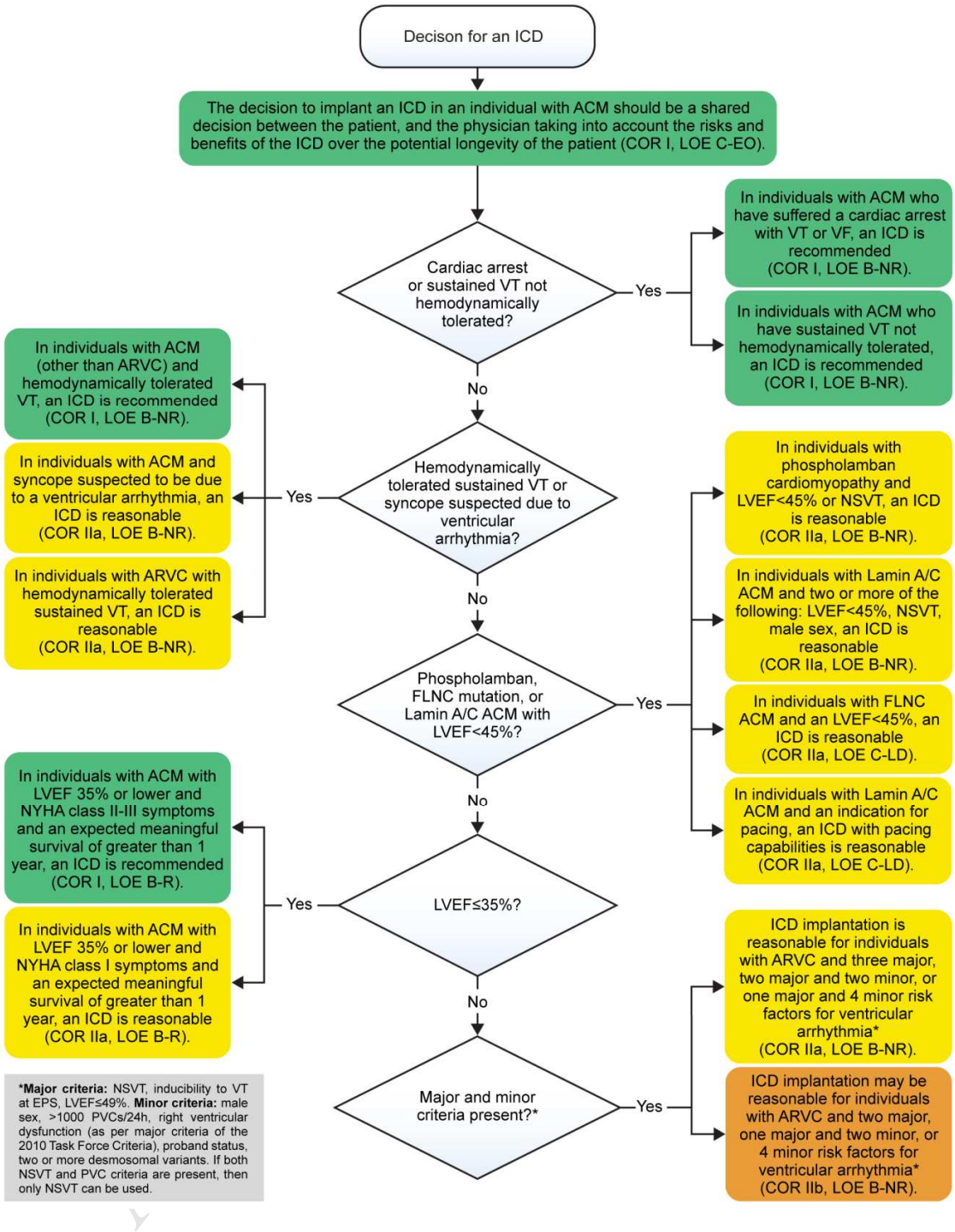


Figure 12. Implantable cardioverter defibrillator (ICD) recommendations. See Section 5 for recommendations regarding left ventricular noncompaction. COR=Class of Recommendation; EPS=electrophysiology studies; FLNC=filamin-C; LOE=Level of Evidence; LVEF=left ventricular ejection fraction; NSVT=nonsustained ventricular tachycardia; NYHA=New York Heart Association; PVC=premature ventricular contraction, VT=ventricular tachycardia. Colors correspond COR in Figure 1.

3.11 Management of Ventricular Arrhythmia and Dysfunction

3.11.1 Medications Including Angiotensin-Converting Enzyme Inhibitors, Beta-Blockers, and Antiarrhythmic Drugs

See Evidence Table: Medical therapy for Ventricular Arrhythmia and Dysfunction. A recommendation flow diagram is shown in Figures 10 and 11.

The aim of medical therapy in ACM is to control the ventricular dimensions and function, manage the congestive symptoms, and prevent and treat the arrhythmia. The management of heart failure in ACM involves two different aspects of myocardial dysfunction: LV failure and RV failure.

3.11.1.1 Medical Therapies for Left Ventricular Failure

ALVC that phenotypically overlaps with classic DCM predominantly affects the left ventricle. In this case, the treatment of symptomatic and asymptomatic heart failure with reduced ejection fraction (HFrEF) in the left ventricle follows the current 2013 (updated in 2016) AHA/ACC(7,8) and European Society of Cardiology (ESC) guidelines.(9) Guideline-directed therapies include angiotensin-converting enzyme (ACE) inhibitors and angiotensin receptor blockers (ARBs), beta-blockers, aldosterone antagonists, and, in selected cases, vasodilators (hydralazine and isosorbide dinitrate).(8,9,192) The 2016 recommendations of the AHA/ACC(7) and ESC guidelines(9) include new drugs: the angiotensin receptor-neprilysin inhibitor (valsartan/sacubitril(193)) and the sinoatrial modulator, ivabradine.(193,194) The therapy for congestive symptoms includes loop diuretics and volume control, with recommendations for a low-sodium diet.(8,9) The benefit of digitalis for symptoms in patients with sinus rhythm has been debated; however, a recent retrospective analysis of the randomized Digitalis Investigation Group trial suggested that patients with LVEF <40% (HFrEF) and patients with LVEF 40%–50% (HF with mid-range ejection fraction, HFmrEF) had a benefit in terms of mortality and hospitalization (HFmrEF) or hospitalization only (HFrEF) from digitalis therapy.(195) Additionally, Patients with reduced LVEF may benefit from cardiac resynchronization therapy, (196) LV-assist devices, and heart transplantation.(8,9) In a systematic review of 4 studies evaluating the use of digitalis for RV failure, which were limited to patients with cor pulmonale, there was no evidence of benefit in terms of improvement in right ventricular ejection fraction (RVEF), exercise capacity, or NYHA class.

3.11.1.2 Medical Therapies for Right Ventricular Failure

COR	LOE	Recommendations	References
IIa	C-EO	In individuals with ACM and symptomatic right ventricular dysfunction, the use of ACE inhibitors or ARBs, as well as beta-blockers, aldosterone antagonists and diuretics is reasonable.	
IIb	C-EO	In symptomatic individuals with ACM and right ventricular dysfunction, the use of isosorbide dinitrate to reduce preload may be considered.	
The therapy to reverse ventricular remodeling in RV failure (typical of ARVC) is less established due to the lack of trials specifically addressing patients with ARVC. In an ARVC model of plakoglobin knockdown in mice, the preload-reducing treatment using a combination of diuretics and isosorbide dinitrate prevented the development of ARVC induced by endurance exercise training.(197) These data suggest a potential benefit of preload-reducing therapy in early stages of RV remodeling.			

3.11.1.3 Antithrombotic Therapy in ACM

COR	LOE	Recommendations	References
I	B-NR	For individuals with ACM, in the presence of atrial fibrillation, intracavitary thrombosis or venous/systemic thromboembolism, anticoagulant therapy is recommended	(198)
Patients with ARVC can develop “atrial disease” and predisposition to atrial tachyarrhythmias. In the absence of atrial fibrillation, however, there is no clear evidence of a benefit from anticoagulation compared with placebo or aspirin in heart failure.(199,200) Specifically in the ARVC population, a study of 126 patients with ARVC found a relatively lower risk of thromboembolism in ARVC compared with LV heart failure; however, patients with severely dilated and hypokinetic right ventricles with slow blood flow and spontaneous echocardiographic contrast were at higher risk.(198) Overall, anticoagulation is appropriate for			

the ACM population (ALVC and ARVC) to reduce the stroke risk in patients with atrial fibrillation in accordance with the current ACC/AHA and ESC guidelines for the management of atrial fibrillation,(201,202) intracavitary thrombosis, and venous or systemic thromboembolism. In the absence of these factors, however, there is no evidence of a benefit from anticoagulation compared with placebo or aspirin.

COR	LOE	Recommendations	References
IIb	C-EO	Antithrombotic therapy may be reasonable in individuals with left or right ventricular aneurysm	
ACM may carry an increased risk of thromboembolic events. In ALVC risk is increased by intraventricular thrombus formation in severe left ventricular dysfunction, and in ARVC by not only RV dysfunction but also localized aneurysms and sacculations Furthermore, some patients with ARVC can develop “atrial disease” and predisposition to atrial tachyarrhythmias. There are no data to indicate antithrombotic therapy in isolated RV dysfunction.			

3.11.1.4 Arrhythmia Management

COR	LOE	Recommendations	References
I	C-LD	Beta-blocker therapy is recommended in individuals with ACM with inappropriate ICD interventions resulting from sinus tachycardia, supraventricular tachycardia, or atrial fibrillation/flutter with high ventricular rate.	(203)
Beta-blocker therapy may prevent the occurrence of supraventricular arrhythmias within the programmed VT detection zone. Inappropriate ICD shocks, which are typically due to supraventricular arrhythmias, are to be avoided, and studies of heart failure patients have demonstrated improved outcomes when the number of inappropriate shocks is reduced.(204-206) There are no randomized studies on specific beta-blockers in ACM. In the general population with heart failure, a nonrandomized *post hoc* substudy of the Multicenter			

Automatic Defibrillator Implantation with Cardiac Resynchronization Therapy (MADIT-CRT) trial showed the effectiveness of beta-blockers (carvedilol in particular) in reducing the number of inappropriate ICD therapies for patients who received an ICD with or without biventricular pacing.(203)

COR	LOE	Recommendations	References
IIa	C-EO	Beta-blocker therapy is reasonable in individuals with ACM who do not have an ICD.	

In patients clinically affected by ACM, beta-blockers can prevent adrenergic arrhythmias, exercise-induced arrhythmias, and ventricular remodeling, although there are no controlled clinical trials to unequivocally demonstrate the drugs' benefit. In a cohort of well-characterized individuals with ARVC, beta-blockers were not significantly effective.(183) In unaffected carriers (genotype-positive or phenotype-negative), the lack of information currently does not support long-term beta-blocker therapy

COR	LOE	Recommendations	References
IIb	B-NR, C-LD	Amiodarone (LOE B-NR) and sotalol (LOE C-LD) may be reasonable in individuals with ACM for control of arrhythmic symptoms or to reduce ICD shocks.	(183,207,208)

In patients with ventricular arrhythmias, antiarrhythmic therapy can be used to control symptoms. In a study of 95 patients with ARVC, the most effective drug appeared to be amiodarone,(207) whereas there was no significant evidence for the efficacy of sotalol and beta-blockers. In a more recent series of 301 ARVC patients, however, neither beta-blocker, amiodarone, nor sotalol reduced life-threatening arrhythmic events.(183)

Given that patients with ARVC are predominantly younger than conventional heart failure patients, sotalol therapy before amiodarone in the earlier phases of the disease can be justified to avoid long-term use and prevent the adverse extracardiac effects of amiodarone, although there are no robust data to support this approach in this ARVC patient population.

The Optimal Pharmacological Therapy in Implantable Cardioverter Defibrillator Patients (OPTIC) trial randomized 412 patients with an ICD (but not specifically ACM) and inducible or spontaneous VT or VF to treatment with amiodarone with a beta-blocker, sotalol alone, or a beta-blocker alone(208). Sotalol showed a trend to reduce all-cause ICD shocks at 1 year from 38.5% to 24.3% (HR: 0.61; *P*=.055). Patients treated with sotalol should have a normal or near-normal QT interval at baseline, and normal or near-normal renal function. Compared with beta-blocker therapy alone, amiodarone reduced the number of ICD therapies (HR 0.27; *P*<.001)(208) but this came at the cost of more adverse effects.(43)

COR	LOE	Recommendations	References
IIb	C-LD	Flecainide in combination with beta-blockers and in the absence of other antiarrhythmic drugs may be reasonable in individuals with ACM, an ICD, and preserved left and right ventricular function for control of ventricular arrhythmias that are refractory to other therapies.	(209)

In a small series of patients, the addition of flecainide in combination with sotalol or metoprolol was found to be effective for controlling ventricular arrhythmias in patients with an ICD and ARVC refractory to single-agent therapy and/or catheter ablation.(209) Data from patients with CPVT, including a recent randomized trial,(210) also suggest the efficacy of flecainide in these patients, which could be extrapolated to the population with ARVC.(211) Overall, these findings suggest the potential benefit of flecainide in combination with beta-blockers for patients with refractory ventricular arrhythmias.

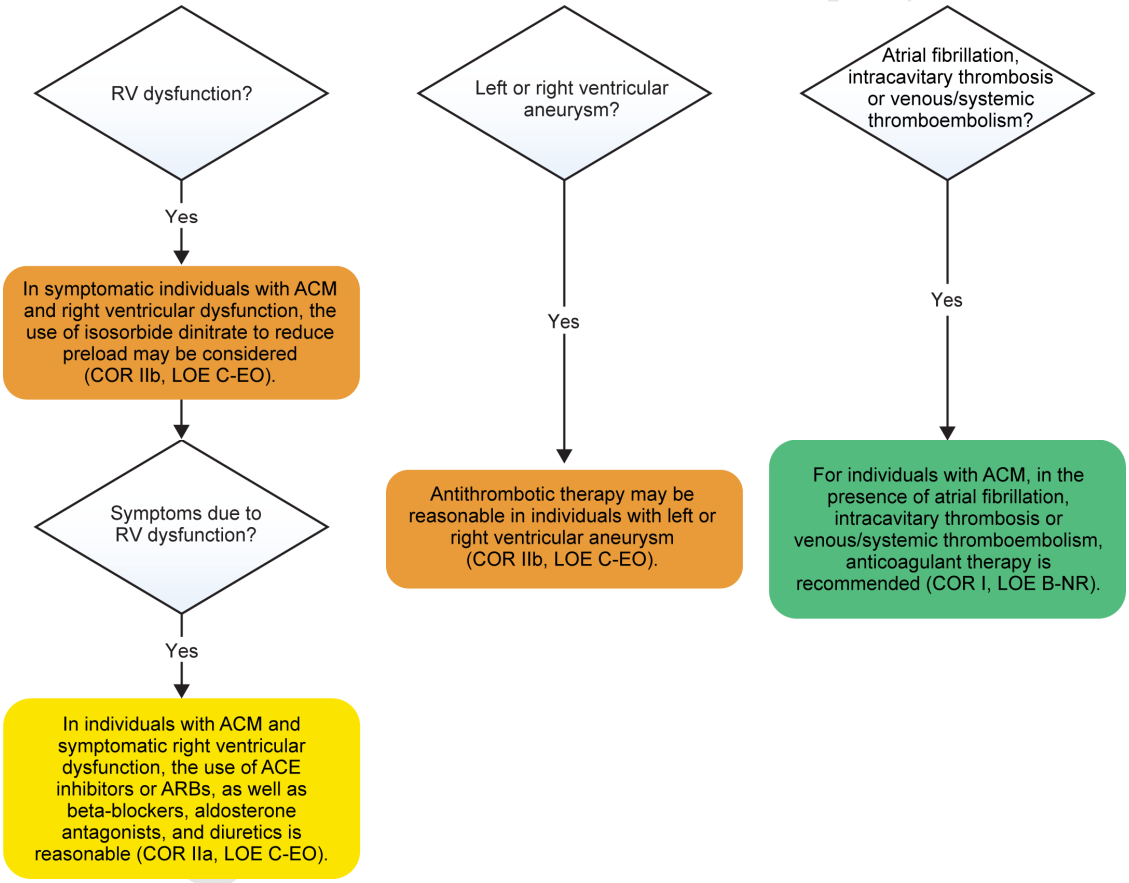


Figure 13. Recommendations for ventricular dysfunction and antithrombotic medical therapy in individuals with arrhythmogenic cardiomyopathy (ACM). ACE=angiotensin-converting enzyme; ARBs=angiotensin II receptor blockers; COR=Class of Recommendation; LOE=Level of Evidence RV=right ventricular. Colors correspond to COR in Figure 1.

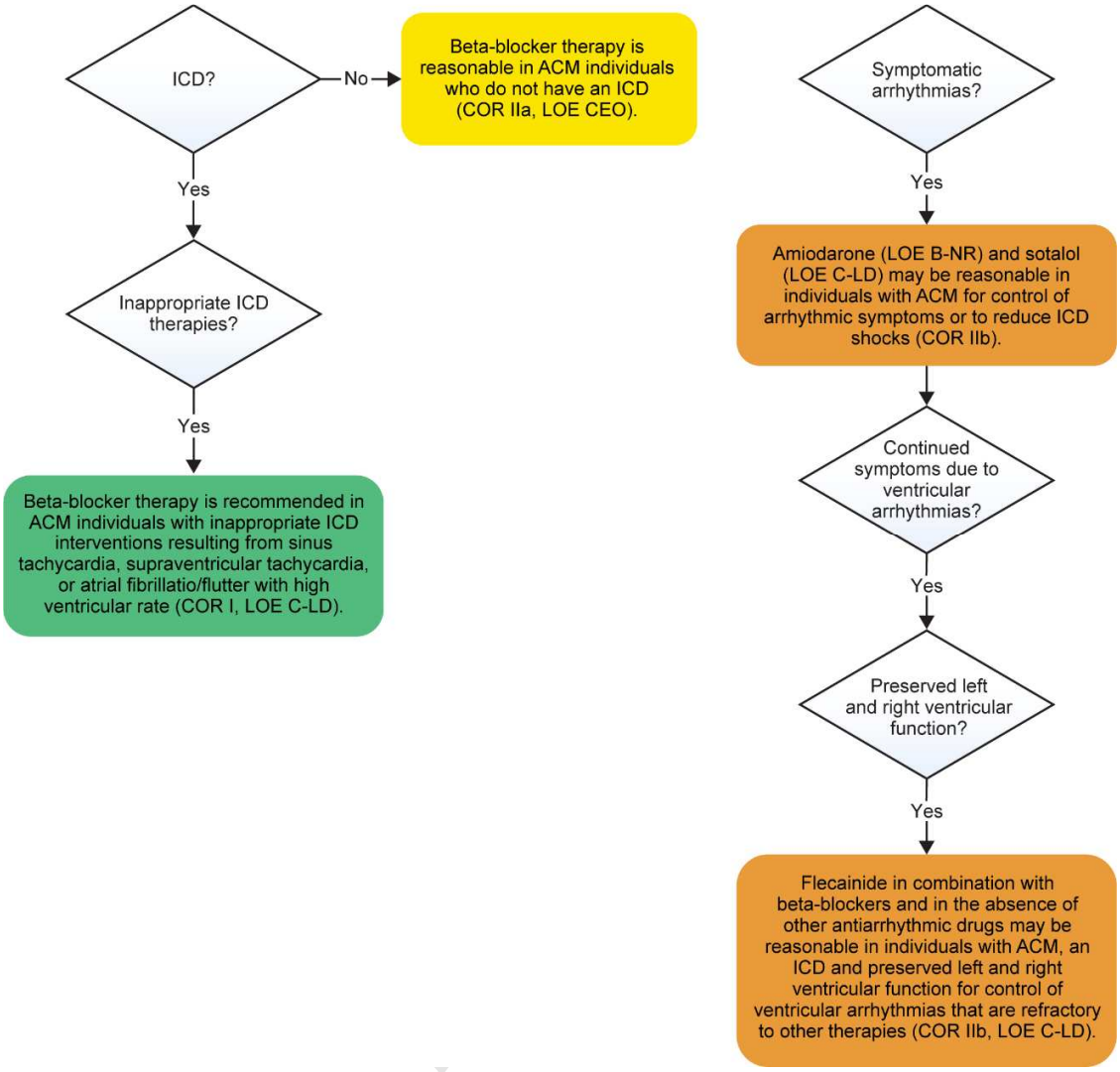


Figure 14. Medical therapy recommendations for arrhythmias. ACM=arrhythmogenic cardiomyopathy; COR=Class of Recommendation; ICD=implantable cardioverter defibrillator; LOE=Level of Evidence. Colors correspond to COR in Figure 1.

3.11.2 Role of Catheter Ablation

See Evidence Table: Catheter Ablation. A recommendation flow diagram is shown in Figure 15.

COR	LOE	Recommendations	References
IIa	B-NR	In individuals with ACM and recurrent sustained monomorphic VT who have failed or are intolerant of amiodarone, catheter ablation is reasonable for reducing recurrent VT and ICD shocks.	(212-222)

Catheter ablation is a well-studied therapy for almost all forms of cardiomyopathy, especially for patients with ischemic scars and those with idiopathic dilated cardiomyopathies.(223-225) Catheter ablation is recognized as a central treatment option for patients with ventricular arrhythmias who have received therapies from their ICDs, and in the context of failure or intolerance of antiarrhythmic drugs.(213,214) For ARVC, evidence from single-center and multicenter cohorts has demonstrated the effectiveness of ablation in reducing the incidence of recurrent VT events and ICD shocks.(218-222)

Although the outcomes are dictated more by the underlying arrhythmogenic substrate and the disease process, there are nevertheless similarities in the pathophysiology and strategies for catheter ablation across all forms of structural heart disease. Compared with patients with healthy hearts, patients with structural heart disease (including those with ischemic heart disease, DCMs, and all forms of ACM) all retain a diseased ventricular myocardium and various degrees of fibrosis or scars. These are fundamental substrates for reentrant ventricular arrhythmia and can therefore be targeted if the patient presents with monomorphic VT.(226-229) Ablation for all forms of structural heart disease is aimed at removing or ameliorating this arrhythmogenic element, and extrapolation is therefore employed in this section, given the limited data for the rare or less-defined cardiomyopathies. Catheter ablation of VT associated with LMNA cardiomyopathy is associated with poor outcomes, including a high rate of arrhythmia recurrence, progression to end-stage heart failure, and high mortality.(230) There are only isolated case reports for catheter ablation of VT in patients with LVNC,(231,232) cardiac amyloidosis,(233,234) and Fabry disease(235); the bulk of the data concern procedural approaches and outcomes for patients with arrhythmogenic RV dysplasia or cardiomyopathy.(216,218-222,236,237)

COR	LOE	Recommendations	References
IIa	B-NR	In individuals with ACM and recurrent symptomatic sustained VT in whom antiarrhythmic medications are ineffective or not tolerated, catheter ablation with availability of a combined endocardial/epicardial approach is reasonable.	(216,218-222)
IIa	C-EO	In symptomatic individuals with ACM and a high burden of ventricular ectopy or nonsustained VT in whom beta-blockers and/or antiarrhythmic medications are ineffective or not tolerated, catheter ablation with availability of a combined endocardial/epicardial approach is reasonable.	
Unlike many ischemic cardiomyopathies in which the diseased substrate is easily accessed transvenously, arrhythmogenic RV dysplasia and cardiomyopathy frequently require an epicardial approach, which is directly related to the location of the diseased tissue.(216,218-222,236,237) This particular approach has been relatively well-studied in terms of outcomes and technical approach. Freedom from ventricular arrhythmias and ICD therapies is definitively improved with combined endocardial and epicardial ablation. Interrupting the diseased substrate and targeting the clinical VT have provided higher long-term success rates of approximately 60%–80%. Therefore, a combined endocardial and epicardial approach is helpful when targeting symptomatic ventricular arrhythmias. These recommendations do not address the separate question of how to approach a patient who has already failed an endocardial approach or whether an epicardial approach should be employed as the first line.			

COR	LOE	Recommendations	References
IIb	C-LD	Individuals with ACM and recurrent symptomatic sustained VT in whom medical therapy has not failed may be considered for catheter ablation.	(216,218,220)

In some catheter ablation studies of patients with ACM, antiarrhythmic drug therapy was not mandated for inclusion. However, the number of such patients included in these studies was limited. This recommendation addresses patients with recurrent symptomatic sustained VT who desire ablation either as first-line treatment or to reduce or avoid medical therapy that has been effective.

Current technology and techniques suggest that electroanatomical mapping supports better outcomes, which is routinely employed at all major centers. These methods are routinely employed to more accurately define scars and disease. Ablations for the more unusual cardiomyopathies are performed at high-volume referral centers, which are more accustomed to the idiosyncrasies of each cardiomyopathy subtype. These centers provide highly trained operating room staff, anesthesiologists, and surgical backup.

Catheter ablation for patients with ARVC should not be considered curative for the underlying arrhythmogenic substrate and is ultimately aimed at improving quality of life by limiting symptomatic ectopy, sustained arrhythmia, and especially ICD therapies. There are insufficient data showing disease progression is affected, sudden death is prevented, or mortality is reduced.

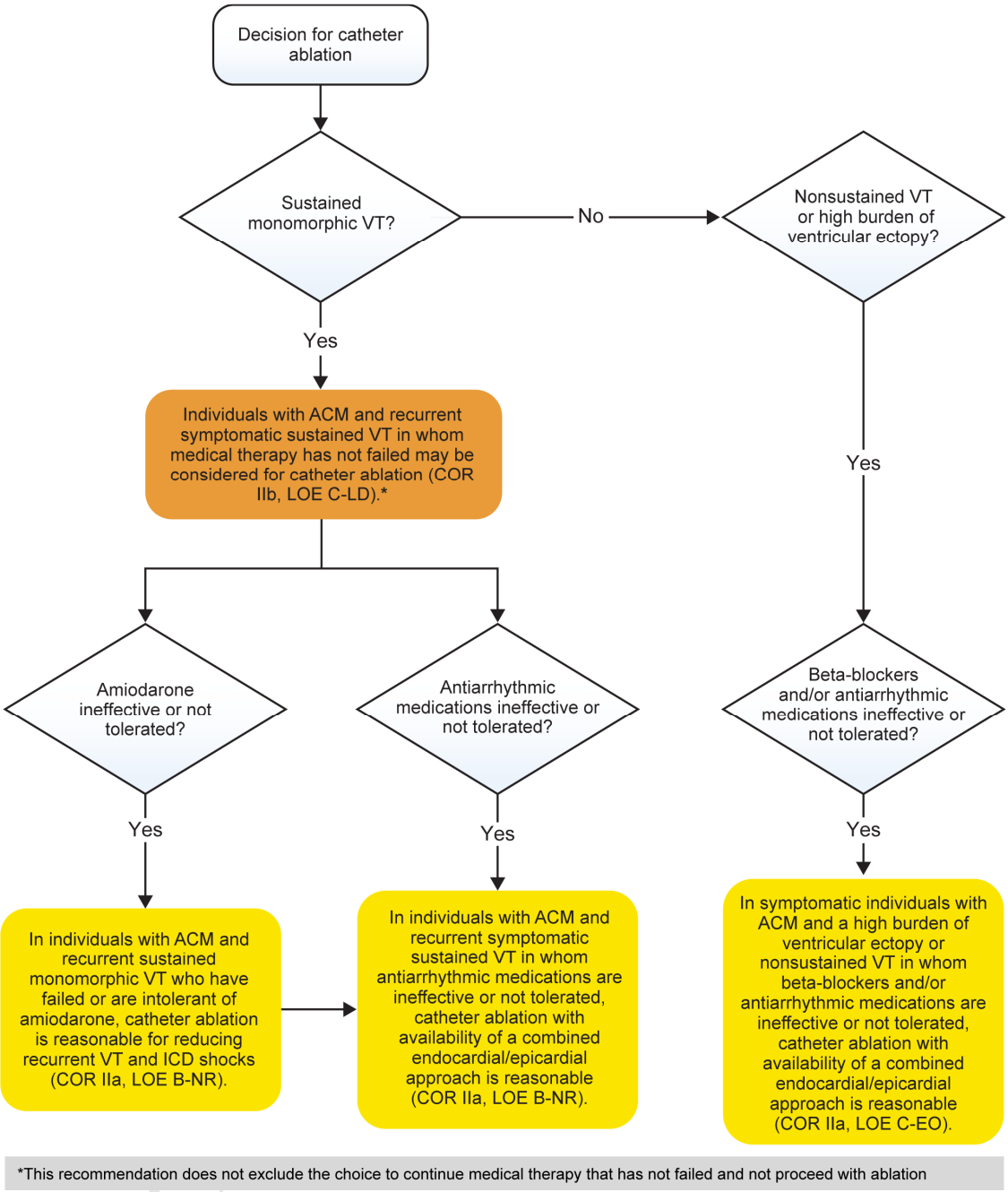


Figure 15. Catheter ablation recommendations for individuals with ACM. ACM=arrhythmogenic cardiomyopathy; COR=Class of Recommendation;ICD= implantable cardioverter defibrillator; LOE=Level of Evidence; VT=ventricular tachycardia. Colors correspond to COR in Figure 1.

3.12 Prevention of Disease Progression

See Evidence Table: Exercise Restriction. A recommendation flow diagram is shown in Figure 16.

Clinicians have long recognized that ARVC patients were disproportionately athletes(238) and that athletic patients with ARVC have a high risk of SCD.(239) A seminal review of autopsies in Italy showed that participation in competitive athletics resulted in a more than 5-fold increase in SCD risk among adolescents and young adults with ARVC(240) and that implementing a preparticipation screening program resulted in a sharp decline in deaths.(241)

The discovery that pathogenic variants in genes encoding the cardiac desmosome were present in up to 60% of patients with ARVC provided insight into the connection between exercise and ARVC. (145) Murine ARVC models with abnormal expression of desmosomal proteins have consistently shown exercise-induced or exercise-exacerbated cardiovascular phenotypes.(242-246) Defining the molecular mechanisms of this process is an active area of research.

These discoveries also prompted research to more precisely define the role of exercise in penetrance, arrhythmic risk, and structural progression in patients with ARVC and their at-risk relatives. These studies (reviewed below) make a compelling case that (1) there is a dose-dependent relationship between exercise exposure and ARVC onset (penetrance) and severity; and (2) frequent high-intensity or competitive exercise in patients with established ARVC is associated with worse clinical outcomes.

3.12.1 Clinical Exercise Questions to Direct a Literature Search

1. In this section, we used the PICO format to construct questions to direct a literature search. The following questions were analyzed: Should a family member who is mutation-positive but phenotype negative be restricted from strenuous exercise to prevent ARVC disease expression?
2. Should patients who meet Task Force Criteria for the diagnosis of ARVC, regardless of symptoms or disease severity, be restricted from strenuous exercise, compared to no restriction, to prevent VT or VF?
3. Should patients who meet Task Force Criteria for the diagnosis of ARVC, regardless of symptoms or disease severity, be restricted from strenuous exercise, compared to no restriction, to prevent progression of RV or LV dysfunction?

3.12.2 Exercise Definitions

To best translate the results of these studies to clinical practice, it is important to consider how each study collects exercise history and defines an individual as an athlete. Physical activity has 4 broad dimensions: (1) mode or type of activity; (2) frequency; (3) duration; and (4) intensity.(247) Activity can be considered recreational or competitive and categorized based on peak static and dynamic demand. Here, we define "endurance" exercise as that with a moderate or high dynamic demand as per the AHA/ACC Scientific Statement for Eligibility and Disqualification Recommendations for Competitive Athletes with Cardiovascular Abnormalities(248) (class C and B activities). Similarly, we define "competitive exercise" as "participation in an organized team or individual sport that requires regular competition against others as a central component, places a high premium on excellence and achievement and requires some form of systematic (and usually intense) training," consistent with these guidelines.(249)

Intensity, duration, and frequency of aerobic physical activity can be integrated into one measure (metabolic equivalent [MET]-minutes/week) for an exercise "dose". For instance, the AHA minimum recommended exercise for healthy adults is 450–750 MET-minutes weekly.(250) A MET is the ratio of the work metabolic rate to the resting metabolic rate. Vigorous-intensity activities are generally considered those requiring ≥6 METS.(251) The 2011 Adult Compendium of Physical Activities provides a comprehensive listing of the METs associated with a variety of physical activities (https://sites.google.com/site/compendiumofphysicalactivities/)(252) Figure 17 includes examples of METS associated with common types of endurance exercise.

3.12.3 Exercise Increases Age-Related Penetrance Among Genotype-Positive Relatives

Evidence from several retrospective studies suggests there is a dose-dependent relationship between endurance exercise and the likelihood of developing ARVC. A study of 87 carriers of heterozygous desmosomal variants showed that participation in vigorous endurance athletics and a longer duration of annual exercise were associated with an increased likelihood of ARVC diagnosis and of developing sustained ventricular arrhythmias.(253) Endurance athletes were defined as participants in a sport with a high dynamic demand(248) for at least 50 hours per year at vigorous intensity. A separate analysis using the same definitions(171) further showed that ARVC patients with adolescent onset were significantly more likely to have been endurance athletes during their youth than were patients with ARVC diagnosed as adults. Finally, a third study confirmed that in 10 families with a segregating *PKP2* variant, family members who

developed ARVC were more likely to be athletes and to have engaged in a significantly higher exercise dose across their lifespan than family members without disease.(254)

Consistent with this, Saberniak et al (255) showed that athletes (1440 MET-minutes/week for a minimum of 6 years) were more likely to be diagnosed with ARVC, and the age of starting athletic training was correlated with age of ICD implantation, suggesting a temporal relationship between the timing of exercise exposure and disease onset. This study also illustrated a linear relationship between the amount of physical activity and the extent of RV and LV dysfunction in patients and at-risk family members. Among asymptomatic family members, athletes had worse LV function and more RV abnormalities. It is important to recognize that most of these data are from carriers of *PKP2* variants, and the association between exercise and penetrance in carriers of other desmosomal and nondesmosomal ARVC-related variants awaits confirmation.

Nonetheless, taken together, these studies establish that the likelihood that genotype-positive relatives of patients with ARVC will develop disease is strongly associated with frequent endurance exercise. Thus, presymptomatic genetic testing not only facilitates early diagnosis but also provides the opportunity to decrease the risk of developing ARVC through lifestyle changes. Clinicians should counsel these patients that competitive or frequent high-intensity endurance exercise is associated with an increased likelihood of developing ARVC.

3.12.3.1 Exercise for Carriers of Pathogenic Variants Detected Incidentally

It is important to recognize that these data are from genotype-positive patients who are also relatives of ARVC patients. ARVC-associated pathogenic variants are increasingly identified through population-based sequencing studies and direct-to-consumer genetic testing.(11) The desmosomal genes are also included in the list of 59 genes recommended by the ACMG for return when discovered as secondary findings.(162) Research suggests that the penetrance of variants detected in this setting is lower than for family members identified through cascade testing.(163) The benefit of limiting frequent high-intensity or competitive endurance exercise for these patients may thus be lower but requires further study.

3.12.3.2 Exercise and Relatives of "Gene-Elusive" Patients with ARVC

Evidence is emerging that there is a cohort of athletic ARVC patients without pathogenic variants who may have a largely exercise-induced form of disease. These patients are characterized by very high levels of athletic activity, no identifiable pathogenic desmosomal

variant, and an absence of family history.(256,257) Unaffected family members of such patients with a normal initial evaluation may have a considerably lower likelihood of developing ARVC. These patients should undergo cardiac evaluation every 1-3 years as described in Section 3.9. At present, however, there is no strong evidence to recommend limiting exercise.

3.12.3.3 Exercise Increases Arrhythmic Risk and Structural Dysfunction in Patients with ARVC

In contrast to the still-limited data available to inform recommendations for patients with a positive genetic test for ARVC but who are phenotype-negative (genotype-positive, phenotype-negative), a growing group of studies have consistently shown that competitive or frequent high- intensity endurance exercise is associated with a higher risk of ventricular arrhythmias regardless of genotype.(183,253,255,256,258,259) Although the definitions of athletic activity vary across these studies, the outcomes are the same, with participation in high-intensity, strenuous, competitive, high-duration exercise associated with poorer survival free from sustained ventricular arrhythmias. This result is not surprising, given that data from autopsy studies have shown that ARVC-related SCD often occurs with vigorous exercise.(260,261) Recently, Lie et al(259) further established that while high-intensity and long-duration exercise were associated with ventricular arrhythmias, intensity remained an independent predictor after adjusting for duration, highlighting the importance of limiting high-intensity exercise.

Several studies have suggested that the risk of arrhythmias during follow-up can be modified by reducing exercise. Desmosomal variant carriers who reduced their exercise after the clinical presentation had lower incidents of ventricular arrhythmia compared with patients who continued to participate in intense and/or long-duration exercise .(253) This finding was replicated in a study of 108 probands from the North American ARVC Registry that showed patients who continued self-defined competitive exercise had a significantly worse arrhythmic course.(258) In contrast, there were no significant differences in the risk of ventricular arrhythmias or death between the inactive patients and the recreational athletes, although recreational athletes had worse LV function. Finally, Wang et al(262) showed that, among 129 ARVC patients with ICDs, patients who reduced their exercise dose (MET-hours/year) the most had the best survival from ICD therapy in follow-up. These data suggest that gene-elusive patients and those who have had an ICD implanted for primary prevention may benefit the most from reducing their exercise dose.

The extent of both RV and LV structural dysfunction is also correlated with exercise history for patients with ARVC. This finding was first observed by Sen-Chowdhry et al(80), who found that, of 116 patients with ARVC, the 11 patients who participated in long-term endurance training had more severe RV dysfunction. Sawant et al showed that among nondesmosomal "gene-elusive" patients with ARVC, those who had performed a higher average MET-hours-year of exercise were most likely to have major RV structural abnormalities.(256) Saberniak et al performed an extensive analysis and demonstrated that RV and LV function was significantly reduced in athletes and that exercise was correlated with the extent of structural dysfunction in a dose-dependent fashion.(255) Although no study has prospectively assessed the effect of exercise reduction on structural progression, athletic activity is associated with poor clinical outcomes. Saberniak et al showed that only athletes progressed to transplantation, while James et al showed that only athletes developed class C heart failure.(253,255)

3.12.4 Exercise and Other Arrhythmogenic Cardiomyopathies

In contrast to ARVC, there are limited genotype-specific data from which to make exercise recommendations for other ACMs. Similar to desmosomal and "gene-elusive" ARVC patients, ventricular arrhythmias occur disproportionately during exercise in patients with the R14del *PLN* variant.(161) Preliminary studies suggest, however, that a history of athletics is not associated with disease penetrance in these patients.

COR	LOE	Recommendations	References
I	B-NR	Clinicians should counsel adolescent and adult individuals with a positive genetic test for ARVC but who are phenotype negative that competitive or frequent high-intensity endurance exercise is associated with increased likelihood of developing ARVC and ventricular arrhythmias.	(171,253-255)
Competitive or frequent high-intensity endurance exercise increases the risk of developing RV and LV dysfunction. Athletic activity prior to and after disease presentation also increases the risk of ventricular arrhythmias and is associated with poorer survival from sustained ventricular arrhythmias.(171,253-255) A positive genetic test indicates a pathogenic or likely pathogenic variant in an ARVC-associated gene per the ACMG guidelines for variant adjudication.(95)			

COR	LOE	Recommendations	References
III: Harm	B-NR	Individuals with ARVC should not participate in competitive or frequent high-intensity endurance exercise as this is associated with increased risk of ventricular arrhythmias and promoting progression of structural disease.	(80,171,183,253-255,258)
Competitive or frequent high-intensity endurance exercise is related to the extent of RV and LV dysfunction in patients with ARVC. Additionally, such exercise is associated with poorer outcomes for ventricular arrhythmias, whereas reducing exercise has a more favorable arrhythmic prognosis. Aiding patients and at-risk family members in making choices about participation in various types of exercise involves ongoing discussion and shared decision making.			

Competitive exercise includes participation in "an organized team or individual sport that requires regular competition against others as a central component, places a high premium on excellence and achievement, and requires some form of systematic (and usually intense) training" as defined by the AHA/ACC Scientific Statement for Eligibility and Disqualification Recommendations for Competitive Athletes with Cardiovascular Abnormalities.(249)

Endurance exercise includes class C and B sports in these guidelines (248). Data on the effect of static exercise (Class A) on outcomes are largely absent from the literature. **Intensity** is typically measured in METS.(252)

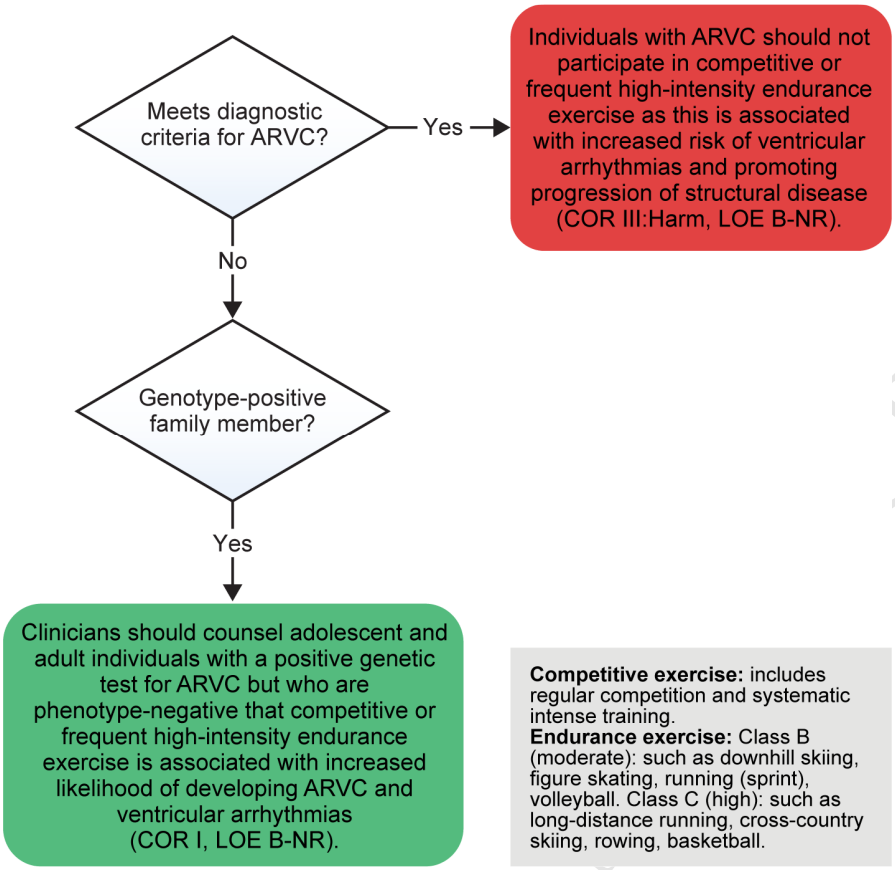
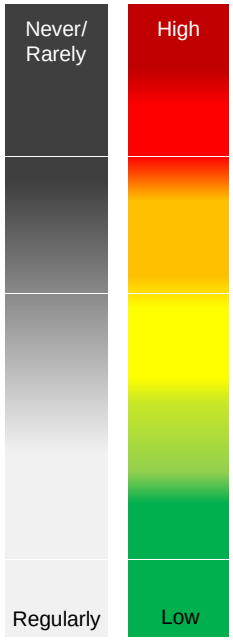


Figure 16. Exercise recommendations for individuals with ARVC. ARVC=arrhythmogenic right ventricular cardiomyopathy; COR=Class of Recommendation; LOE=Level of Evidence. Colors correspond to COR in Figure 1.



METS	Examples of METS associated with endurance exercise
16	Competitive cycling
15	Cross-country ski racing (>8.0 mph)
12	Canoeing, rowing, crew in competition
10	Soccer, competitive
9.8	Running–6 mph (10 minutes/mile)
8	Basketball game
7	Racquetball
5.8	Swimming laps, freestyle–light-moderate effort
5.3	Downhill skiing–moderate effort
5	Walking for exercise–4 mph (very brisk pace, level, firm surface)
4.8	Golf
3.5	Walking for pleasure or transportation
3.3	Sailing (boat and board sailing, windsurfing, ice sailing)
3	Canoeing/rowing for pleasure
2.5	Yoga

Figure 17. Metabolic equivalents (METS) Associated with Common Types of Endurance Exercise (https://sites.google.com/site/compendiumofphysicalactivities/).(247,252) Inverse association between intensity of exercise (METS) and recommended frequency of participation among patients with ARVC. Aiding patients and at-risk family members in making choices about participation in various types of exercise involves ongoing discussion and shared decision making. Based on data suggesting that higher exercise intensity and doses (intensity*duration) are associated with poorer outcomes(254,255,258,259), vigorous-intensity activities (red/orange) should be performed rarely if at all, and lower-intensity activities (green) more regularly. This figure is provided to aid the clinician in understanding METS associated with a variety of common activities(252) and to aid in discussions with patients and families.

For the basic science details of the mechanisms responsible for the forms of ACM, please see Section 4 Disease Mechanisms, below.

Section 4 Disease Mechanisms

An overview of some of the disease mechanisms for arrhythmogenic cardiomyopathy is shown in Figure 18.

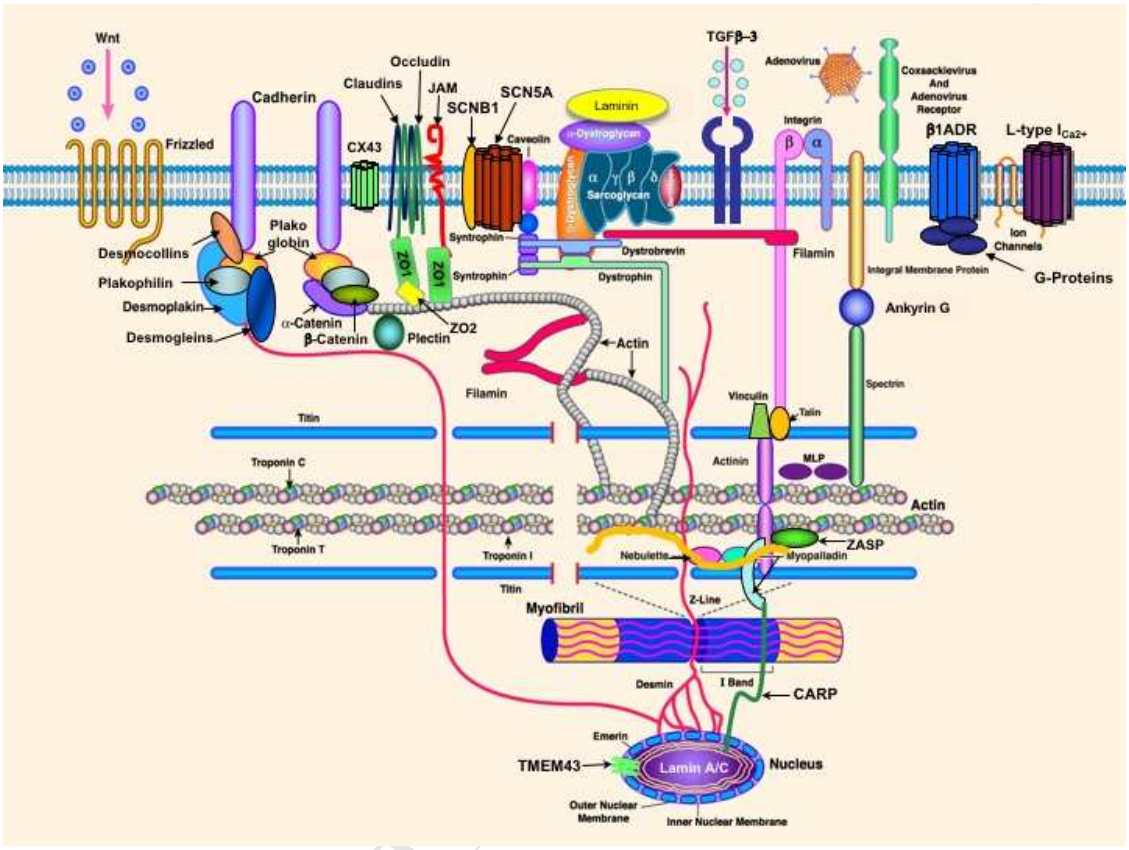


Figure 18. Disease mechanisms for arrhythmogenic cardiomyopathy. Cardiomyocyte showing the extracellular matrix, sarcolemma, sarcomere, nucleus, and key proteins that provide structure for ventricular function and cardiac rhythm. See the description of the functions of these proteins in section 4.1 Desmosomal Defects.

4.1 Desmosomal Defects

The cardiac intercalated disc (ID) is a highly organized structure that connects adjacent cardiomyocytes and is classically comprised of three main structures: (1) gap junctions (GJs), which metabolically and electrically connect the cytoplasm of adjacent cardiomyocytes; (2) adherens junctions (AJs), which connect the actin cytoskeleton of adjacent cells; and (3) desmosomes, which function as cell anchors and connect intermediate filaments. In addition, ion channels reside in the ID. Pathologic genetic variants in ID proteins have been associated with cardiac arrhythmias, such as BrS, ARVC, and other genetically determined ACMs.(263,264)

However, rather than being independent, all ID components work closely together by partnering with multifunctional proteins such as ZO-1, ankyrin G, and β-catenin, allowing the ID to integrate mechanical and electrical functions. GJs form a plaque surrounded by the perinexus in which free connexons reside; the connexome integrates sodium (Na_V) channels, the desmosome, and GJs; and the area composita hosts AJs and desmosomes, also integrated as adhering junctions. Furthermore, the transitional junction connects sarcomeres to the plasma membrane. The ID ensures rapid propagation of the electrical signal that initiates contraction throughout the heart and allows the cardiomyocytes to withstand the strong mechanical forces imposed by the beating of the heart. AJs, desmosomes, GJs, and ion channels form a functional unit as the area composita. Furthermore, GJs and ion channels likely create and propagate action potentials (APs) together. Some structural components of cell–cell junctions can also interact with other ID proteins or function in signaling pathways, such as Cx43 and β-catenin. Protein deficiencies can ultimately lead not only to mechanical dysfunction (eg, AJ dysfunction) but also to arrhythmias, often via GJ remodeling, thereby illustrating the interdependency of ID components and the coupling of mechanical and electrical elements.

The lateral membrane (LM) of cardiomyocytes has a different makeup compared to the ID, hosting, among others, costameres and focal adhesions and linking sarcomeres to the extracellular matrix. The ID and LM have several proteins in common, such as vinculin and α-actinin, and ion channels.

The AJ is the primary anchor for myofibrils and connects actin filaments from adjacent cells, which allows the cell to retain its shape under mechanical stress. Furthermore, the AJ transduces signals concerning the actin cytoskeleton and senses mechanical forces on the cell. The transmembrane protein N-cadherin is the main constituent of AJs and homodimerizes with N-cadherins from adjacent cells in the extracellular space, acting as an intercellular zipper. This action provides tissue specificity during development, allowing cells to interact only with cells expressing the same cadherin. Calcium ions ensure the rod shape of N-cadherin, the intracellular domain which primarily binds β-catenin. N-cadherin also possesses regulatory functions including a role in mechanosensing. β-catenin directly interacts with the C-terminal cytoplasmic domain of N- cadherin. By associating with α-catenin and vinculin, β-catenin connects AJs to the actin cytoskeleton.

β-catenin also plays a central role in cadherin-mediated signaling and can activate the canonical Wnt signaling pathway. β-catenin translocates to the nucleus when Wnt binds its Frizzled receptor, to initiate transcription of transcription factors of the T-cell factor/lymphoid enhancer-binding factor family. The canonical Wnt pathway is crucial in cardiac development but has also been proposed as the key mechanism in certain cardiomyopathies, (ie, activation induces cardiac hypertrophy).Therefore, N-cadherin has been thought to sequester β- catenin to prevent Wnt activation. Activation of the Wnt pathway increases expression of the GJ protein Cx43, and the C-terminus of Cx43 can interact with β- catenin. When Wnt is not present, cytoplasmic β-catenin is targeted for degradation by the proteasome.

Although AJs also transduce forces to the cytoskeleton, desmosomes are more robust, thanks to their connection to mechanically resilient IFs. The intercellular part of the cardiac desmosome is built up by the cadherins desmoglein-2 (DSG2) and desmocollin-2 (DSC2), which bind in a heterologous way. The armadillo proteins junction plakoglobin (JUP) and plakophilin-2 (PKP2), and desmoplakin (DSP), (a member of the plakin superfamily) connect desmin to the desmosome. When DSC2 and DSG2 are bound, the hyperadhesive state of the desmosome depends on the presence of calcium ions.

Considering the major desmosomal proteins, PKP2 is associated with GJs and is required for the organization of ID and desmosomal function. Together with JUP, PKP2 mediates attachment to IFs. PKP2 knockdown causes a decrease in conduction velocity and an increased propensity to develop re-entry arrhythmias, whereas *PKP2* variants are most common in hereditary ACM. Plakoglobin is present in both desmosomes and AJs. Desmoplakin connects the desmosomes to the type III IF protein desmin, and its N- terminal and C-terminal domains and the α-helical domain in between are each almost 1000 amino acids long and interaction with PKP2 occurs at their N-terminal domains. *DSG2* pathogenic gene variants are, like all other cardiac desmosomal proteins, associated with ACM.

The most prominent ACM desmosomal gene mutations include *PKP2* and *DSP*, with desmosomal cadherins *DSG2* and *DSC2*, and *JUP* being less common.(14,25,169,265) The majority of these genes primarily cause ARVC, although pathogenic variants in *DSP* cause a substantial amount of ALVC. Other “non-desmosomal” genes, such as *TGFB3* and *TMEM43*, disrupt the function of desmosomes(132,266,267). One of the more recently described causitive genes is CDH2, encoding N-cadherin, another member of the cadherin superfamily of predominantly Ca^{2+}-

dependent cell surface adhesion proteins.(118,119) In the report by Mayosi et al, the affected family members all presented with ventricular arrhythmias and demonstrated imaging features of ARVC. The study by Turkowski et al, however, described a family with an arrhythmogenic presentation who all showed an cardiomyopathy in the imaging study.(119) In desmosomes, desmosomal cadherins (desmocollin and desmoglein) are mainly anchored to the IFs of the cytoskeleton through numerous intracellular protein partners, whereas in fascia AJs, the classical cadherin N-cadherin is primarily anchored to the actin microfilaments of the cytoskeleton and promotes cell–cell adhesion through extracellular associations of its cadherin repeat domains.(268-270) Interestingly, the protein components of desmosomes and fascia AJs are not mutually exclusive.(270,271) In fact, the mechanical junctions of the ID are an admixture of desmosomal and fascia adherens proteins that form a hybrid functional zone, the area composita.(269,272,273) Therefore, even if ARVC has been traditionally considered as a desmosomal disease, it is now reasonable to consider that the mechanistic basis of ARVC may extend beyond the strict functional zone of the desmosome, to that of the area composita. Supporting this concept, pathologic variants in *CTNNA3* (another gene in the area composita*)*, which encodes for αT-catenin, has also been identified in patients with ARVC who were negative for pathologic variants in the main desmosomal genes.(115) Alpha-catenins are natural partners of the cytoplasmic domain of classical cadherins, that is, N- and E-cadherins and, in the case of N-cadherin, act as its go-between for anchoring to the actin cytoskeleton.

The fact that cadherin-2, like its desmosomal cadherin counterparts, is a major player in the ID is also supported by the *cadherin-2* cardiac-specific mouse model with deletion of N-cadherin in the adult mouse heart causing dissolution of the ID structure, including loss of both desmosomes and AJs, demonstrating that desmosome integrity is also cadherin-2 dependent.(274) These mice also exhibited modest, albeit atypical, DCM and spontaneous ventricular arrhythmias that resulted in SCD.(274) This increased arrhythmic propensity (all mice experienced SCD approximately 2 months after deleting N-cadherin from the heart) was probably due to a reduced and heterogeneously distributed connexin-43, causing loss of functional GJs and partial cardiomyocyte uncoupling and highlighting the prominent role of cadherin-2 in all types of functional junctions in the ID.(275) GJ decreases in number and size, with concomitantly increased arrhythmia susceptibility, have also been demonstrated in the context of N-cadherin heterozygous null mice, with 30%–60% of these mice developing VT, suggesting that cadherin-2 haploinsufficiency might create an important arrhythmogenic

substrate.(276) ID remodeling with concomitant reduction of localization of desmosomal proteins, connexin-43, and cadherin-2, has also been demonstrated in ventricular tissues of transplanted hearts of patients with ARVC, further supporting the involvement of cadherin-2 in ARVC pathogenesis.(277)

4.2 Ion Channel Defects

Cardiac cells are excitable cells that can generate and propagate an AP, the electrical signal that induces cardiomyocyte contraction. The cardiac AP is generated by ions moving across the cell membrane that, by depolarization, takes the cell from the resting state to an activated state and then, by repolarization, back to the resting membrane potential.(278) All phases of the cardiac AP occur via the synergistic activation and inactivation of several voltage-dependent ion channels. In contractile cardiomyocytes, APs are triggered by the acute entrance of sodium ions (Na^+) inside the cell, resulting in an inward current (I_{Na}) (*SCN5A*) that shifts the membrane potential from its resting state (−90 mV) to a depolarization state (+20 mV). This phase is followed by the efflux of potassium (K^+) ions through an outward current named I_{to}, which initiates cell repolarization. This in turn is followed by the plateau phase, a short period of constant membrane potential due to the balance between inward calcium (Ca^{2+}) currents (I_{CaL}) through the voltage-dependent L-type calcium channels (LTCCs) and time-dependent delayed-rectifier outward K^+ currents (mainly slow delayed-rectifier I_{Ks} [KCNQ1] and rapid delayed-rectifier I_{Kr} [KCNH2]). At this point, the Ca^{2+} entry through the LTCC triggers a much larger release of Ca^{2+} from sarcoplasmic reticulum (SR) stores through the ryanodine receptor channel type 2, producing a systolic increase in the intracellular Ca^{2+} needed for cell contraction. Upon LTCC inactivation, the net outward K^+ currents repolarize the cell and bring the membrane potential to its resting state. The balance between Ca^{2+} and K^+ currents therefore determines the AP duration. The basal and acetylcholine-dependent inwardly rectifying K^+ currents (I_{K1} and I_{KACh}) control the final repolarization and determine the resting membrane potential. Ca^{2+} is then extruded from the cell through the Na^+/Ca^{2+} exchanger (NCX) type 1 and taken back into the SR through the SR Ca^{2+}-ATPase type 2a, thereby restoring low intracellular Ca^{2+} levels, allowing cell relaxation during diastole.

Pacemaker cells are distinct from other cell types in showing automaticity, a property resulting from both voltage- dependent and calcium-dependent mechanisms.(279) The former involves the funny current (I_f) carried by hyperpolarization-activated cyclic nucleotide-gated

channels,(280) which have several unusual characteristics, such as activation on hyperpolarization, permeability to sodium and potassium ions, modulation by intracellular cyclic adenosine monophosphate, and a small single-channel conductance. The latter involves spontaneous calcium release from the SR,(281) which activates I_{NCX}. The crucial role of calcium-dependent mechanisms has been demonstrated in mice with complete atrial-specific knockout of NCX, which has shown no pacemaker activity.(282) Both mechanisms result in spontaneous depolarization responsible for the rising slope of the membrane potential. When the proper ion current flows are disturbed, electrical abnormalities in the form of arrhythmias occur.

4.2.1 *SCN5A*

The *SCN5A* gene, which encodes the alpha subunit of the voltage-gated sodium channel $Na_v1.5$, is responsible for the inward sodium current (I_{Na}).(283) This current is the main component of rapid depolarization in cardiomyocytes and is responsible for the AP upstroke, which subsequently initiates the multistep excitation–contraction coupling cascade.(284) This periodic depolarization underlies the synchronous and rhythmic contraction of the heart chambers.(284)

Pathologic variants in genes encoding for ion channel proteins are well-known causes of inherited arrhythmia disorders, such as LQTS, short QT syndrome (SQTS), BrS, CPVT, and AV block, to name a few. The involved genes include those encoding for the cardiac sodium channel, potassium channels, and calcium channels. In these disorders, pathologic variants in the affected gene result in disturbance of the function of the encoded ion channel protein, leading to abnormalities in the function of the AP. In several of these genes, pathologic variants can cause a heterogeneous array of clinical features, at times differing even within the same family. For instance, pathologic variants in the cardiac sodium channel gene *SCN5A* are responsible for LQTS type 3 (LQT3), which develops due to a gain in channel function. On the other hand, pathologic *SCN5A* variants also cause BrS, an electrocardiographically distinguishable disorder compared with LQT3, which occurs due to a loss of sodium channel function.(285) In addition to causing ventricular tachyarrhythmias, atrial fibrillation, atrial standstill, and AV block,(286) *SCN5A* is known to cause an arrhythmogenic form of DCM and an arrhythmogenic form of LVNC.(287)

The 2006 Scientific Statement on “Contemporary definitions and classification of the cardiomyopathies”, endorsed by the AHA, placed “ion channel disorders” under the classification of primary genetic cardiomyopathies.(288) This decision was largely based on data

regarding the role of pathologic variants in genes encoding defective ion channel proteins, governing cell membrane transit of sodium, potassium, and calcium ions leading to ion channel-related arrhythmia disorders, including LQTS, SQTS, BrS, and CPVT and the role of these disorders in the development of cardiomyopathies. (288)This classification scheme has continued to be evaluated, and the list of overlapping cardiomyopathy–arrhythmia phenotypes has grown over time, with primary and secondary causes of ion channel dysfunction seen in many cardiomyopathies. Pathogenic variations in the *SCN5A* gene, resulting in electrical and structural cardiac remodeling, such as in arrhythmogenic DCM, was first described in 2003 by Groenewegen et al in a large family with atrial standstill, a rare form of atrial cardiomyopathy.(289) At the same time, it was shown that the clinical spectrum of rare *SCN5A* pathologic genetic variants could be expanded to ARVC and DCM, accompanied by arrhythmias and conduction disorders.(131,290) In 2008, new evidence showed that pathologic variants in the SCN5A gene might represent a risk factor for rhythm disturbances in LVNC.(291) These disorders are inherited as autosomal dominant traits. The frequency of *SCN5A*-mediated cases in patients with ACMs is approximately 2%(292); however, when pathologic variants in the *SCN5A* and *LMNA* genes are taken together, they account for up to 5%-10% when considering only patients with DCM with progressive cardiac conduction defects and supraventricular and/or ventricular arrhythmias. Both RV and LV dilation and dysfunction can occur, as can broad and heterogeneous electrical abnormalities, including atrial standstill, progressive AV block, atrial fibrillation, sick sinus syndrome, VT, torsades de pointes, and VF, resulting in arrhythmic sudden death in some cases.

SCN5A may also play a role in ACM without having pathogenic gene variants. In ARVC, it is clear that when pathologic variants in genes encoding the cardiac desmosome are identified, $Na_v1.5$, which has been shown to co-precipitate with the desmosomal protein *PKP2*, can be disrupted and dysfunctional. The loss of *PKP2* expression has been shown to alter the amplitude and kinetics of the sodium current (I_{Na}).(293) In addition, pathologic variants in *PKP2* have been associated with a sodium channelopathy phenotype, whereas decreased immunoreactive $Na_v1.5$ protein has been detected in the majority of human ARVC heart samples.(294) These observations indicate a close functional association between $Na_v1.5$ and mechanical junction proteins, which is further supported by the finding that $Na_v1.5$ coprecipitates with the AJ protein N-cadherin(295) and demonstrating the presence of “adhesion/excitability” nodes formed by aggregates of $Na_v1.5$ and N-cadherin.(296) Leo-Macias et al. described the presence of these

adhesion/excitability nodes in cardiac myocytes and demonstrated that (1) the AJ protein N-cadherin serves as an attractor for $Na_v1.5$ clusters, (2) the $Na_v1.5$ in these clusters are major determinants of the cardiac sodium current, and (3) clustering of $Na_v1.5$ facilitates its regulation by molecular partners.(296) Te Riele et al further demonstrated that $Na_v1.5$ is in a functional complex with cell adhesion molecules and that a primary $Na_v1.5$ defect can affect N-cadherin biology, resulting in reduced size and density of N-cadherin clusters at the ID.(295)

The finding that $Na_v1.5$ coprecipitates with the AJ protein N-cadherin demonstrates the link to the junction/ID/desmosome and supports the hypothesis that sodium channel dysfunction can occur via disruption of binding partners being mutated (ie, supporting the PKP2 and arrhythmia scenario). Therapy for this disorder has not been well studied and is not standardized. Pacemakers and ICDs have been used for some individuals with varying outcomes. Pharmacologic therapies have been disappointing, and no specific pharmacotherapy has thus far been recommended for these patients.

4.3 Cytoskeletal Defects

The cytoskeleton is the cell's basic scaffold in which other subcellular components are spatially arranged so as to communicate efficiently between the cell's internal and external environments. In striated muscle cells, the cytoskeleton consists of myofibrillar and extramyofibrillar portions. The myofibrillar cytoskeleton is composed of thin and thick myofilaments and titin filaments, providing the foundation for myocyte contraction and relaxation. The extramyofibrillar cytoskeleton consists of microfilaments, microtubules, and IFs.

IFs serve as a scaffold connecting the sarcomere to other organelles (such as mitochondria or the nucleus) to maintain cellular integrity and contribute to mechanotransduction. The sarcomere is tethered to the sarcolemma (the membrane surrounding the myofibril) by another cytoskeletal assembly—the costamere. Costameres link the sarcomere to the sarcolemma via the Z-disc and M-band. Individual heart cells are connected by IDs, which synchronize muscle contraction. The myofibrils are linked to the plasma membrane at the Z-discs via the costameres. There are specific membrane invaginations (T-tubules) at the Z-disc, which associate with flanking SR to the dyad. At the ID, desmosomes and AJs link neighboring cardiomyocytes mechanically, and GJs provide ion channels for intercellular communication. Desmosomes link to the IF cytoskeleton (composed of desmin), whereas AJs anchor actin

filaments (the myofibrils). The border of the last sarcomere before the plasma membrane is defined as the transitional junction.

The cytoskeletal structure is continually remodeled to accommodate normal cell growth and respond to pathophysiological cues. The cytoskeleton maintains the structural integrity and morphology of cardiomyocytes. Cytoskeleton components are also involved in a variety of cellular processes, such as cell growth and division, cell movement, vesicle transport, cellular organelle location and function, localization and distribution of membrane receptors, and cell–cell communications. The cytoskeleton in cardiac myocytes is also believed to play an important role in the transduction of mechanical signals, based upon the unique distribution of the extensive cytoskeletal network as well as the juxtaposition of ion channels, signaling transducers, and network messengers. Cytoskeletal modifications and cardiac myocyte remodeling are causally linked to cardiac hypertrophy and failure. Abnormalities in cytoskeletal components not only cause structural defects but also impair mechanotransduction. The cytoskeleton not only interacts with the extracellular matrix via transmembrane proteins such as integrins but also registers adjacent Z-discs to one another, to the cell membrane, and to the nuclear envelope through a delicate network. A number of signaling partners bind to the network either directly or via linker proteins. For example, the muscle LIM domain protein gene (*MLP*) encodes a muscle-specific cytoskeletal protein interacting with titin and telethonin (T-cap). Studies in genetically engineered mice with targeted ablation of MLP suggest that the titin–telethonin–MLP complex may serve as a stretch sensor in cardiac muscle cells. There is growing interest in examining the role of cytoskeletal components in ion channel regulation under physiological and pathological conditions.

DCM characterized by ventricular dilatation and diminished contractile function accounts for more than 80% of non-HCMs. DCM has a population prevalence of approximately 1 in 500 and is associated with prognostically adverse arrhythmias at initial disease presentation in up to one-third of patients.(297) While increased age, male sex, and impaired ventricular function are established arrhythmic risk factors, arrhythmias also occur in patients with no known risk factors. Approximately 20%–35% of DCM cases are familial. Although impaired force generation, energy shortage, and compromised calcium homeostasis could cause DCM, impaired force transmission and/or defective mechanotransduction caused by defects in cytoskeletal proteins

such as desmin, lamin A/C, α-actin, δ-sarcoglycan, dystrophin, plakoglobin, desmoplakin, MLP, and telethonin, appear to be a prevalent mechanism underlying DCM.

4.3.1 Myofibrillar Cytoskeleton

The myofibrillar cytoskeleton is composed of thin and thick myofilaments of the sarcomere as well as titin filaments, providing the foundation for myocyte contraction and relaxation. The basic unit of a myofibril is called the sarcomere and is defined as the region between two Z-discs. The actin crosslinker protein α-actinin is a classical marker for Z-discs; however, Z-discs house a large number of other cytoskeletal and signaling proteins. The sarcomere, which is the smallest contractile unit of striated muscle, has its lateral boundaries defined by the protein-dense Z-discs that cross-link the barbed ends of actin-based thin filaments from adjacent sarcomeres via α-actinin and are bordered by the I-band, the region on either side of a Z-disc that is devoid of myosin-containing thick filaments. The A-band comprises the region extending the entire length of the thick filaments, and the M-band resides at the center of the A-band. The force of muscle contraction occurs when the myosin motor protein attaches to the actin filament and pulls the Z-discs toward the M-band. The sarcomere is not a static structure and responds to alterations in muscle load and injury. Z-discs also serve as an anchor site for the N-terminus of titin and nebulin and nebulette filament systems, making it indispensable for transmitting contractile force.

Z-discs anchor the thin filaments, which are composed of actin, tropomyosin, and the troponin complex. Tropomyosin and the troponin complex are crucial for contraction regulation at the thin filament level, which is triggered by calcium. The thick filaments are composed of myosin dimers (a myosin consists of a myosin heavy chain and two myosin light chains), which are arranged in bipolar filaments, with the myosin tails making up the central region of the sarcomere and the head interdigitating with the thin filaments. Myosin-binding protein C is associated with a subset of the myosin heads and contributes to controlling contraction at the thick filament level. The third filament system is called the elastic filaments and consists of titin.

Variants in Z-disc-associated proteins are linked to numerous cardiomyopathies and skeletal myopathies.(298-301) Alpha-actinin is the predominant Z-disc protein. There are four vertebrate α-actinin genes with overlapping functions; however, only *ACTA2* is found in cardiac muscle.(302) The N-terminal actin-binding domain is linked to an α-actinin-2 homodimer cross-linking two antiparallel actin filaments of adjacent sarcomeres, forming a flexible tetragonal

lattice.(303) This lattice is essential for the rigidity that the Z-disc requires to serve as a structural anchor site, while still allowing for the flexibility needed to conform to contractile forces.

Alpha-actinin has a myriad of binding partners, with each interaction serving a distinct role in the production of concerted contractile action. The major Z-disc proteins that interact with *ACTA2* include actinin-associated LIM protein, muscle LIM protein, the N-terminus of titin, myotilin, CapZ, Z-band alternatively spliced PDZ-motif protein (ZASP), filamin, α-actinin, and telethonin-binding protein of the Z-disc, myopalladin, and myopodin.(304-306) Independent studies have reported that human variants in the *ACTA2* gene are associated with DCM, HCM, idiopathic VF, LVNC, and atrial arrhythmias.(307)

Filamin protein family members also bind and cross-link actin. There are three filamin proteins: filamin-A (α isoform), filamin-B (β isoform), and striated muscle-specific filamin-C (γ isoform). Filamin-C (γ-filamin) is one of the major proteins that serves as a link between the costamere and Z-disc and is involved in signal transduction with integrins. Filamin-C functions through interactions with sarcolemmal muscle cell membrane proteins such as γ-and δ-sarcoglycans of the dystrophin glycoprotein complex(308)), the β1A-subunit of the integrin receptor complex,(309) and Z-disc proteins (such as myotilin(310) and FATZ(309,311,312)). *W2710,* an autosomal dominant nonsense variant, p.Trp2710*, in the last exon of the human filamin-C gene interferes with its dimerization process and causes filamin-C to aggregate within skeletal muscle fibers, a phenomenon that eventually leads to myofibrillar myopathy.(313,314)

Many of the proteins within the myofibrillar cytoskeleton have been shown to cause cardiac and/or skeletal myopathy. Review of the details on the patients with pathologic variants in the genes encoding these proteins with disturbance of protein function, has demonstrated a significant association with early-onset arrhythmias, conduction system disease, and sudden cardiac arrest or death, consistent with an arrhythmogenic form of cardiomyopathy.

4.3.2 LIM domain-binding 3-encoding Z-band Alternatively Spliced PDZ motif

ZASP/LDB3 is one of the major components of the Z-disk proteins in cardiac muscle(315) and plays an important role in stabilizing the Z-disk structure through its PDZ-mediated interaction with α-actinin-2, the main component of the Z-disk actin cross-linker, and F-actin, the main cytoarchitectural protein of cardiomyocytes.(316) Global ablation of the murine ZASP homolog

cypher can disorganize the sarcomere and cytoskeleton, leading to severe cardiomyopathy and skeletal myopathy in mice and humans,(317) whereas cardiac-specific ablation of *cypher* can cause DCM and SCD.(318) The product of *SCN5A*, the $Na_v1.5$ current, localizes at the cardiomyocyte membrane along the sarcomeric Z-lines via α-actinin-2, thus connecting $Na_v1.5$ to actin filaments.(319) ZASP/telethonin contributes to localizing $Na_v1.5$ to the T-tubule membrane at the Z-line, creating a multiprotein complex associated with α-actinin-2. Variants in the *ZASP/LDB3* gene have been shown to cause abnormalities in sodium channel function.

Vatta et al were the first to describe pathologic variants in *ZASP/LDB3* in patients with DCM and LVNC, identifying 6 (6%) of 100 probands screened.(126) Pathologic variants in *ZASP/LDB3* were identified in 2 families and 4 sporadic cases. Of the 9 familial and sporadic patients affected, 3 had early-onset conduction system abnormalities and ventricular arrhythmias, including sinus bradycardia, second-degree AV block, PVCs, VT, intraventricular conduction delay, ventricular bigeminy, and LBBB. Subsequent reports on patients with arrhythmias and conduction disease associated with DCM and LVNC have supported the causative connection with variants in *ZASP/LDB3*. Arimura et al(320) reported on a family with 6 affected members who developed DCM between 50 and 69 years of age, consistent with late-onset DCM, 3 of whom died suddenly. Xi et al(321) studied one of the original *ZASP/LDB3* pathologic variants reported by Vatta et al(126) and demonstrated several underlying mechanisms by which the *ZASP-D117N* variant (a *ZASP/LDB3* variant identified in patients with DCM/LVNC associated with intraventricular conduction delay, ventricular bigeminy, and LBBB) can cause intraventricular conduction delay: (1) ZASP1-D117N can cause loss of function of $Na_v1.5$ in human cell lines, and in neonatal cardiomyocytes; (2) *in silico* simulation using the Luo-Rudy model showed that the extent of functional disturbances of $Na_v1.5$ caused by *ZASP-D117N* is sufficient to delay cardiac conduction in human hearts; (3) the interaction between ZASP and $Na_v1.5$ requires preservation of the Z-disk protein complex; and (4) the modification of $Na_v1.5$ by ZASP-D117N occurs without significant disruption of Z-line structures in cardiomyocytes.(321)

Although $Na_v1.5$ preferentially localizes at the intercalated disc via SAP97 and lateral membranes via the dystrophin-associated protein complex (2 pools), localization at the T-tubular system also occurs.(322,323) Upon posttranslational modification, $Na_v1.5$ remains attached to the cytoskeleton linked to multiprotein complexes and stored in subcellular compartments. $Na_v1.5$ is also known to localize at the cardiomyocyte membrane along the

sarcomeric Z-lines via α-actinin-2, thus connecting $Na_v1.5$ to actin filaments.(319) The study by Xi et al therefore suggests that electrical remodeling may precede anatomical remodeling in DCM/LVNC associated with ZASP with the loss of function of $Na_v1.5$ by the mutated ZASP, occurring without significant disruption of cytoarchitectural networks(321). This is particularly important in a clinical situation, since patients who carry *ZASP-D117N* may develop arrhythmias even before manifesting heart failure symptoms. The loss of function of $Na_v1.5$ by ZASP-D117N appeared to be largely responsible for the conduction delay.

More recently, Lopez-Ayala et al reported on a family in which a pathologic variant in *ZASP/LDB3* was associated with ARVC.(158) The index patient and their first-degree and second-degree relatives underwent a complete clinical evaluation. After ruling out pathologic variants in the 5 desmosomal genes, genetic testing using next-generation sequencing was performed on the proband, who had a long-standing history of presyncope. The index patient experienced syncope associated with sustained VT that required electrical cardioversion to restore sinus rhythm. Her ECG showed complete RBBB, with inverted and flat T waves in the precordial leads, echocardiogram, and CMR showing biventricular dilation and severe biventricular systolic dysfunction; midwall LGE affecting the LV was also identified. An ICD was recommended. However, the patient died in the operating room during the surgical procedure as a result of an anesthetic complication. The postmortem examination demonstrated extensive fibro-fatty replacement in the right ventricle, extensive fibrosis in the left ventricle, and limited inflammatory patches, consistent with a diagnosis of ARVC. A heterozygous pathogenic missense variant in *ZASP/LDB3* (c.1051A>G) was identified, and another 6 carriers were identified in her family via cascade screening. Three of these relatives fulfilled the criteria for a definitive diagnosis of ARVC, and another reached a borderline diagnosis. These relatives had symptoms including frequent palpitations, abnormal ECGs that showed inverted T waves in right precordial and inferior leads, signal-averaged ECGs that showed late potentials, 24-hour Holter monitoring studies that showed runs of idioventricular rhythm and ventricular ectopic beats, CMR that showed a dilated right ventricle with severe systolic dysfunction, and normal left ventricle with no LGE. A number of the relatives were started on beta-blockers. Based on this family, the authors suggested a direct link between ACM with biventricular involvement and pathogenic variants in *ZASP/LDB3*.

4.3.3 Alpha-Actinin-2

Alpha-actinin-2 is a prominent member of the Z-disc found in cardiac muscle, has an N-terminal actin-binding domain, and creates a lattice-like structure that is essential for the rigidity that the Z-disc needs to serve as a structural anchor site, while still allowing for the flexibility needed to be responsive to contractile forces.(303,324,325) The protein's primary function is to anchor and crosslink actin filaments in the cardiac Z-disc at the lateral boundaries of the sarcomere.(306) The Z-disc provides structural support by tethering the sarcomere to the sarcolemma via the costameres and by anchoring filamentous F-actin, titin, and nebulette.(305)

As one of the integral Z-disc proteins, α-actinin has a myriad of binding partners, with each interaction serving a distinct role in the production of concerted contractile action.(306) The major Z-disc proteins that interact with α-actinin-2, smooth muscle (ACTA2), are actinin-associated LIM protein, muscle LIM protein, the N-terminus of titin, myotilin, CapZ, ZASP, filamin, and telethonin-binding protein at the Z-disc, myopalladin, and myopodin. ACTA2 has also been demonstrated to bind phosphorylase-b, an important metabolic enzyme in the Z-disc. Furthermore, there is evidence that α-actinin-2 (ACTN2) directly interacts with cardiac ion channels (such as the potassium ion channels KCNA4 and KCNA5(326,327) and the sodium ion channel SCN5A(319)) and forms a bridge between the calcium ion channels CACNA1C and CACNA1D.(328) Thus, disruption of ACTN2 may affect the localization and function of cardiac ion channels. The authors speculated that the various clinical presentations of Ala119Thr result from a stochastic disruption of one of the many functional roles of ACTN2.

One presentation of ACM was reported by Bagnall et al, who performed exome sequencing on a four-generation family with idiopathic VF, LVNC, and sudden death and identified a pathologic variant in the ACTN2 gene.(329) Clinical evaluation of the family identified marked cardiac phenotype heterogeneity, with some individuals being asymptomatic and others having LVNC, resuscitated cardiac arrest due to idiopathic VF, DCM, or sudden unexplained death. WES identified an Ala119Thr pathologic variant in the ACTN2 that segregated with disease. The 22-year-old female proband presented syncope and a family history of premature sudden unexplained death (her 25-year-old sister died in her sleep). The proband's ECG showed sinus rhythm with nonspecific ST-T wave changes, and her echocardiogram and cardiac MRI showed prominent LV apical trabeculations with preserved LV systolic function, consistent with LVNC. There were no inducible arrhythmias in the EPS, and her QTc measured 440 ms. The proband was implanted an ICD. Her father had a history of dyspnea, LBBB, and LV dilation with reduced

LVEF (EF of 27%). One of proband's female cousins experienced a resuscitated cardiac arrest; however, her cousin's CMR revealed normal LV and RV indexed dimensions and function, with no evidence of myocardial fibrosis. The cousin was found to have idiopathic VF and was therefore implanted an ICD, which subsequently delivered two appropriate shocks. The cousin responded successfully to quinidine therapy.

In another report, Girolami et al. assessed a large 4-generation Italian family, 18 members of which underwent direct clinical assessment and genetic testing, including the proband.(330) Eleven individuals had evidence of autosomal-dominant cardiomyopathy and had variable combinations of 3 distinctive features: regional LV noncompaction with LV hypertrophy, atrial septal defect, and early-onset supraventricular arrhythmias and AV block. In most of these patients, frequent premature atrial contractions that developed into atrial fibrillation or flutter represented the initial clinical manifestation. These arrhythmic manifestations were an essential part of the phenotypic spectrum. The onset of supraventricular arrhythmias followed a common pattern, initially presenting with very frequent premature atrial contractions, proceeding to paroxysmal atrial fibrillation (between 30–50 years of age) and then to permanent atrial fibrillation, requiring a pacemaker due to slow ventricular conduction. Many of the family members were treated with ICDs. The authors suggested that the ACTN2 pathologic variants may directly participate in the genesis of familial supraventricular arrhythmias.

4.3.4 Filamin-C

Filamin protein family members also bind and cross-link actin. There are 3 filamin proteins, with filamin-C (γ isoform) the only striated muscle-specific protein. In addition to the N-terminal actin-binding domain, there is a Z-disc localization motif(310). Filamin-C is one of the major proteins that serves as a link between the costamere and Z-disc and is involved in signal transduction with integrins. Filamin-C directly interacts with 2 protein complexes that link the subsarcolemmal actin cytoskeleton to the extracellular matrix: the dystrophin-associated glycoprotein complex and the integrin complex. At IDs, filamin-C is located in the fascia adherens where myofiber ends reach the sarcolemma, adjacent to the position of desmosomal junctions. Filamin-C functions through interactions with the sarcolemmal muscle cell membrane dystrophin-associated glycoproteins (such as γ-and δ-sarcoglycans(308)), the β1A-subunit of the integrin receptor complex, and Z-disc proteins (such as myotilin(310) and FATZ(309,311,312)). The participation of filamin-C in the attachment of the sarcomere's Z-disk to the sarcolemma

(costameres) and to the IDs allows cell-to-cell mechanical force transduction. FLNC pathologic variants have been associated with myofibrillar myopathies, as well as cardiomyopathies.

Ortiz-Genga studied the *FLNC* gene using NGS in 2877 patients with inherited cardiovascular diseases,(34) with clinical and genetic evaluation of 28 affected families. The authors identified a characteristic phenotype in probands with truncating variants in *FLNC*, as well as 23 truncating pathologic *FLNC* variants in 28 probands previously diagnosed with dilated, arrhythmogenic, or restrictive cardiomyopathy. The authors also identified 54 pathologic variant carriers among 121 screened relatives. The phenotype consisted of LV dilation (68%), systolic dysfunction (46%), and myocardial fibrosis (67%) in the imaging test, as well as inferolateral negative T waves, low QRS voltages, and ventricular arrhythmias (82%) in the ECG (33%), with frequent SCD (40 cases in 21 of 28 families). The authors observed no clinical skeletal myopathy. Penetrance was >97% in carriers over 40 years of age, and there was an autosomal dominant inheritance pattern. Immunohistochemical staining of myocardial tissue showed no abnormal filamin-C aggregates in patients with truncating *FLNC* pathologic variants. Isolated or predominant RV involvement, common with desmosomal pathogenic variants, was not observed. Unlike patients with pathogenic lamin A/C, emerin, or desmin pathogenic variants, these patients had mild and infrequent cardiac conduction abnormalities. The authors suggested consideration of prompt implantation of a cardiac defibrillator for affected patients harboring truncating pathogenic variants in *FLNC*.

4.3.5 Extramyofibrillar Cytoskeleton

The extramyofibrillar cytoskeleton consists of microfilaments (actin), microtubules, and IFs (desmin) It connects the sarcomere with the sarcolemma and extracellular matrix through the Z-disc and submembrane cytoskeleton,(331-334) thereby ensuring power transmission produced by the sarcomeres. The extramyofibrillar cytoskeleton also provides support for subcellular structures, organizes the cytoplasm, regulates sarcolemma topography, and transmits intercellular and intracellular mechanical and chemical signals.

4.3.5.1 Desmin Filaments

Desmin is the main IF protein and is deemed necessary for cardiomyocyte structural integrity, the allocation and functionality of its mitochondria, the nucleus position, and sarcomere genesis.(334,335) The IFs create a 3-dimensional skeleton covering the entire cytoplasm,

enveloping Z-discs, extending from one Z-disc to another. IFs are also involved with other cell organelles, including the sarcoplasmic reticulum and the T-tubular system. These desmin filaments extend from the Z-disc to the costameres, where they are bound through plectin and dysferlin, extend to the ID, and emerge from the Z-discs of the perinuclear myofibrils to the nuclear membrane.

Desmin is encoded by the *desmin* (*DES*) gene and pathogenic variants in *DES* have been shown to cause severe skeletal and cardiac muscle diseases with heterogeneous phenotypes. *DES* variants have also been found in patients with DCM and ARVC. Brodehl et al(336) identified two novel variants in DES (p.Ala120Asp [c.359C>A] and p.His326Arg [c.977A>G]) in a family with a broad spectrum of cardiomyopathies, with a striking frequency of arrhythmias and SCDs. *In vitro* experiments with desmin-p.A120D identified a severe intrinsic filament formation defect causing cytoplasmic aggregates in cell lines and of the isolated recombinant protein. Model variants of codon 120 indicated that ionic interactions contributed to this filament formation defect. *Ex vivo* analysis of ventricular tissue slices revealed a loss of desmin staining within the ID and severe cytoplasmic aggregate formation, whereas Z-band localization was not affected. The authors proposed that the loss of desmin-p.A120D filament localization at the ID resulted in its clinical arrhythmogenic potential. Bermúdez-Jiménez et al more recently demonstrated impaired filament formation and disruption of cell membrane integrity in a severe form of arrhythmogenic LV cardiomyopathy due to a *DES* pathogenic variant, p.Glu401Asp, in a large family.(337)

Variants in the *DES* gene result in striated muscle disorders characterized by the formation of inclusion bodies, weakening of the desmin cytoskeleton, disruption of subcellular organelle organization, and eventually myofibril degradation. These muscle disorders are referred to as desmin-related myopathy or desminopathy and often present in young childhood, with patients experiencing increasing muscle weakness. These disorders are associated with a wide spectrum of clinical phenotypes, even within the same family, and range from scapuloperoneal, limb girdle, and distal myopathic phenotypes with variable cardiac or respiratory involvement to pure cardiomyopathies.(338)

To date, multiple reports of ACM caused by pathogenic *DES* variants have been published. *DES* variants have been previously reported in conduction disease and cardiomyopathies, in particular cases of DCM(339), and, more recently, in ARVC.(169) The first of these, *DES*

pathogenic variant p.N116S, was identified in a 17-year-old patient with ARVC and concomitant subclinical skeletal muscle alterations, and this variant led to an amino acid substitution that in turn led to aggresome formation in cardiac and skeletal muscle.(340,341) All other reported ARVC-related *DES* variants underlie a clinically heterogeneous phenotype, frequently associated with muscle abnormalities, including a *DES*-p.S13F pathogenic variant identified in 39 family members from 8 Dutch families(169,342) with associated variable skeletal myopathy and a wide spectrum of cardiomyopathies, including 2 patients with ARVC. Another *DES* variant, p.N342D, was described in patients affected with desmin-related myopathies(343). The association of this variant with RV cardiomyopathy was also noted in select patients.(342,344) A *DES*-p.P419S variant was identified by exome sequencing in a large Swedish family, showing myofibrillar myopathy and ARVC (ARVC7 locus).(122) Bermúdez-Jiménez et al described a multigenerational family in which approximately 30 family members affected with an ACM phenotype hosted a rare missense pathogenic variant of the *DES* gene (c.1203G>C; p.Glu401Asp)(337). These members showed that the *DES* Glu401Asp variant caused the disease in the family, with 100% penetrance and variable expressivity. The phenotype presented itself as an arrhythmogenic phenotype with a high risk of SCD and progressive HF. In 4 of the individuals studied, RV involvement was observed, and 2 had epsilon waves. Fibro-fatty infiltration was identified, predominantly in the left ventricle, and the cardiomyocytes had reduced cellular adhesion, reminiscent of the defect found in ARVC, along with reduced expression of DES and cell–cell junction proteins.

4.4 Sarcomeric Defects

The cardiac sarcomere is the fundamental contractile unit of the cardiomyocyte. Genetic variants in sarcomere genes are a well-established cause of HCM and, in some cases, can cause familial DCM, LVNC, and RCM. (345) Variants in MYBPC3 account for approximately 50% of all genotyped HCM cases, with most being loss-of-function variants, whereas missense variants in MYH7 account for 30% of cases.(346,347) Other genes, such as TNNT2, TNNI3, TPM1, ACTC1, MYL2 and MYL3, account for ≤5% of HCM cases each. A recent study investigating variant excess in cases compared with the Exome Aggregation Consortium control population(348) showed variants in MYH7, TNNC1, TNNT2 and TPM1 significantly enriched in patients with DCM.(100) Specifically, MYH7 accounts for approximately 3%–4% of familial DCM cases.(339) Sarcomere gene variants contribute to cases of LVNC, although most often in phenotypes that include

another cardiomyopathy, cardiac malformation and/or reduced ejection fraction, with MYH7 variants contributing the most cases.(349,350) Other genes encoding sarcomeric and Z-disc proteins have also been identified in individuals with LVNC, including *ACTC1, MYBPC3, TNNT2, TPM1, TTN*, and *LDB3*. RCM in childhood can be caused by variants in thin filament genes, *TNNT2, TNNI3*, and *TPM1*. (351)

The presence of a sarcomere variant is associated with worse outcomes in HCM, with patients with sarcomere-positive HCM having poorer survival from major cardiovascular events compared with patients with gene-elusive HCM.(347,352) Similarly, a recent study of LVNC cases showed a greater risk of major cardiovascular events in patients with a sarcomere variant compared with those without. (353) Using NGS, Wang et al targeted and sequenced 73 genes related to cardiomyopathy in 102 patients with LVNC, with 63% of pathogenic variants in sarcomere-encoding genes and 12% in ion channel-encoding genes.(354)

4.5 Metabolic Defects

The clinical manifestations of inherited disorders of fatty acid oxidation vary according to the enzymatic defect and can present as isolated cardiomyopathy (DCM, HCM), sudden death, progressive skeletal myopathy, and hepatic failure arrhythmias, which can be a presenting symptom of fatty acid oxidation deficiencies.(355) Over a 25-year period, Bonnet et al diagnosed 107 patients with an inherited fatty acid oxidation disorder; arrhythmia was the predominant presenting symptom in 24 (22%) of these patients.(355) These 24 cases included VT (n=15), atrial tachycardia (n=4), sinus node dysfunction with episodes of atrial tachycardia (n=4), AV block (n=6), and LBBB (n=4) in newborn infants. The authors observed conduction disorders and atrial tachycardias in patients with defects of long-chain fatty acid transport across the inner mitochondrial membrane (carnitine palmitoyl transferase type II deficiency and carnitine acylcarnitine translocase deficiency) and in patients with trifunctional protein deficiency. Also, VTs seen in patients with any type of fatty acid oxidation deficiency. The authors concluded that accumulation of the arrhythmogenic intermediary metabolites of fatty acids, such as long-chain acylcarnitines, could be responsible for the development of arrhythmias and that inborn fatty acid oxidation errors may cause unexplained sudden death or near-miss sudden death in apparently healthy infants and those with conduction defects or VT. Diagnosis is determined by a serum acylcarnitine profile.

Specifically, inborn fatty acid oxidation errors result in metabolite buildup proximal to the enzyme defect and in deficient formation of energy-yielding substrates after the block. In the defects downstream from carnitine palmitoyltransferase I, the acylcarnitine that accumulates has detergent properties, which may explain its toxicity. Indeed, amphiphilic lipid metabolite, long-chain acylcarnitine, and lysophosphatidylcholine accumulate during myocardial ischemia and play a pivotal role in the production of arrhythmias. Incorporation of long-chain acylcarnitine in the sarcolemma elicited electrophysiological anomalies analogous to those seen in acute myocardial ischemia.(356) The cellular electrophysiological bases of the proarrhythmic effects of long-chain acylcarnitine appear to be multifactorial. First, reduction of the single-channel conductance of the inwardly rectifying K current by amphipathic lipid metabolites may account for automatic AP discharges from the resting and plateau potentials, leading to VT. Second, retardation of conduction velocities by the decrease in excitatory Na current could produce conduction anomalies and yield to reentry.(357) Third, nonesterified fatty acids directly activate voltage-dependent Na currents in cardiac myocytes, inducing cytotoxic calcium overload.(358) Finally, amphipathic metabolites can interfere with the GJs and disturb the cell membrane's lipid-protein interface, thereby impairing GJ channels.(359) These toxic effects on ionic currents have not been observed with short- and medium-chain acylcarnitine.(356)

Systemic primary carnitine deficiency, a carnitine transporter deficiency, occurs when free carnitine cannot be freely filtered by renal glomeruli, in which 95% is supposed to be reabsorbed by the renal tubules by a high-affinity carnitine transporter in the cellular plasma membrane. Carnitine is not catabolized in humans, and its only metabolic conversion is through ester formation, with most esterified carnitine excreted in urine. Active carnitine transport from blood into cells is mediated by the same transporter that functions in the kidneys. The carnitine transporter OCTN2 is encoded by the *SLC22A5* gene and transports carnitine in a sodium-dependent manner.(360,361)

Carnitine transporter deficiency is inherited as an autosomal recessive trait. As a result of its deficiency, carnitine is not reabsorbed in the kidneys, leading to urinary loss and depletion of blood and tissue levels, resulting in severe impairment of long-chain fatty acid oxidation and hypoketotic hypoglycemia with fasting and stress. Age at presentation can range from infancy to adulthood, but neonatal hypoglycemia and sudden death can occur. Clinical manifestations in early-onset disease include chronic or acute skeletal myopathy and cardiomyopathy, typically

exacerbated by metabolic decompensation. Untreated heart disease proceeds to DCM with reduced LVEF or mild interventricular septal hypertrophy. Electrocardiographic findings include abnormal T waves, ventricular hypertrophy, and atrial arrhythmias. Life-threatening arrhythmias can occur, including NSVT with periods of sinus rhythm and ventricular premature beats, even in the presence of only borderline LV hypertrophy. Carnitine supplementation is typically administered at a dose of 200 to 300 milligrams per kilogram body weight divided throughout the day.

4.6 Mitochondrial Forms

The presentation of mitochondrial cardiomyopathy includes HCM, DCM, and LVNC forms,(362,363) and the severity can range from asymptomatic to devastating multisystem disease.(364) Severe cardiac manifestations include SCD, heart failure, and ventricular tachyarrhythmia, which can worsen acutely during a metabolic crisis. Mitochondrial crises are often precipitated by physiologic stressors such as febrile illness and surgery and can be accompanied by acute heart failure. Most patients with neuromuscular symptoms present with normal or slightly elevated creatine kinase levels, a normal electromyogram, and normal results of nerve-conduction studies.(365-367) Abnormal liver enzyme levels have been found in up to 10% of patients.(365,368) Sensorineural hearing loss occurs in 7%–26% of patients, and its prevalence increases with age.(369,370)

Patients with myoclonic epilepsy with ragged red fibers (MERRF) and mitochondrial encephalopathy, lactic acidosis, and stroke (MELAS) should be monitored for the development of cardiac hypertrophy and DCM. Patients with MERRF can present myoclonus, generalized convulsions, cerebellar ataxia, muscular atrophy, and elevated blood lactate and pyruvate levels, as well as ragged red fibers in muscle biopsy specimens. A case series of patients with MERRF and an m.8344A>G variant of mtDNA revealed that early age at onset was the only factor associated with the occurrence of myocardial disease.(371) The development of myocardial disease in this cohort was associated with a higher risk of SCD. Patients with MELAS can also present ragged red fibers in the muscle biopsy; however, unlike patients with MERRF, patients with MELAS have normal early development and start to show symptoms only between 3 years of age and adulthood. Patients with MELAS tend to have short stature, seizures, hemiparesis, hemianopia, and blindness.(372)

Mitochondrial variants are common causes of myocardial LVNC in young children. LVNC is characterized by prominent ventricular trabeculations and deep recesses that extend from the LV cavity to the subendocardial surface of the ventricle, accompanied or not by LV dysfunction.(373-375) Studies have shown the importance of substrate flexibility in preserving normal cardiac function. In experimental models of pressure overload, failing human hearts have shifted from oxidizing fatty acids (the preferred substrate in the healthy heart) to oxidizing glucose for energy production. This metabolic switch is associated with the downregulation of genes involved in mitochondrial biogenesis and fatty-acid metabolism and is mediated by the deactivation of PPAR-α and its activator, PGC-α, which are members of a family of transcriptional coactivators involved in mitochondrial regulation and biogenesis. An increased reliance on glycolytic pathways could effectively reduce oxygen consumption in the short term; over time, however, reduced oxygen consumption might enable the progression of heart disease by creating an energy-deficient state.(376) Experimental evidence has shown that elevated fatty-acid flux and fatty-acid oxidation (FAO)-deficient states can be associated with cardiac dysfunction. Both chronic increases in FAO (as observed in diabetes) and decreases in FAO (as seen in pressure-overload models of heart failure) can lead to heart failure.(377) Accordingly, energy deficiency can be broadly conceived as both a cause and an effect of heart failure.

The management of mitochondrial disease and cardiomyopathy is largely supportive. Physicians should be aware that patients can make a remarkable recovery from a severe crisis state. Pharmacologic strategies include the use of various dietary supplements. A typical “mitochondrial cocktail” would include coenzyme Q10, creatine, L-carnitine, thiamine, riboflavin, folate, and other antioxidants, such as vitamins C and E. Studies have suggested that the use of antioxidants partially improves clinical features.(376,378) In contrast, a systematic review by Chinnery et al found no clear evidence to support the use of any supplement in patients with mitochondrial disease.(379)

The mortality rate can be high for patients with mitochondrial disease that progresses to a crisis state, such as an acute or subacute multiorgan failure secondary to mitochondrial respiratory chain function that worsens due to fever, illness, stress, medications, or heat; urgent treatment is therefore necessary. Crises that can be associated with severe lactate elevations and cardiac complications during a crisis include cardiogenic shock, atrial and ventricular arrhythmias, DCM,

and SCD. Patients often have baseline acidemia, and the correction of acidosis should be gradual. Oxygenation can worsen the crisis by increasing free-radical production; the partial pressure of oxygen therefore needs to be maintained between 50 and 60 mm Hg.(380,381) Patients with mitochondrial disease who present with fever or who are unable to eat or drink may be administered dextrose-containing intravenous fluids—preferably D10 with half-normal saline content—at a maintenance dose, regardless of blood glucose levels. Their metabolic and volume status should be evaluated periodically. The management of these patients' cardiac complications, including heart failure, bradyarrhythmias, and tachyarrhythmia, follows the same guidelines as those for the general population. If cardiac dysfunction is noted during a crisis, patients should be closely monitored using serial echocardiography. In selected patients who have advanced heart failure due to cardiomyopathy, cardiac transplantation may be needed. Three pediatric patients with mitochondrial cardiomyopathy who underwent cardiac transplantation reportedly had excellent early and late outcomes.(382)

4.6.1 Kearns-Sayre Syndrome

Kearns-Sayre syndrome (KSS) is a mitochondrial myopathy characterized by the clinical triad of ptosis, chronic progressive external ophthalmoplegia, and abnormal retinal pigmentation and is associated with cardiac conduction defects and DCM, sometimes requiring transplantation.(383,384) Approximately 50% of patients with KSS have cardiac involvement, including recurrent syncope, bundle branch block, fascicular block, and nonspecific intraventricular conduction disturbances; 20% of deaths in these patients have been attributed to cardiac causes. In a guidelines publication, the ACC/AHA/HRS assigned a class I recommendation (with a LOE B rating) to pacemaker implantation for third-degree and advanced second-degree AV block at any anatomic level when associated with neuromuscular diseases and AV block. Skeletal muscle histopathology commonly demonstrates ragged red fibers. The genetic abnormalities observed in KSS consist largely of single large-scale mitochondrial DNA deletions, although mitochondrial DNA point variants, such as m.3249G>A in the *tRNA (Leu)* gene, m.3255G>A in the *tRNA (Leu)* gene, and m.3243A>G in the *tRNA (Leu)* gene, have also been reported.(384,385)

4.7 Histiocytoid (Oncocytic) Cardiomyopathy

Infantile histiocytoid cardiomyopathy is a rare but distinctive arrhythmogenic disorder characterized by incessant VT, cardiomegaly, and sudden death within the first 2 years of life if

left untreated. Approximately 100 histiocytoid cardiomyopathy cases have been reported in the literature(386-400); however, the prevalence is likely to be higher, given that many cases of histiocytoid cardiomyopathy could have been misdiagnosed as sudden infant death syndrome.(401) Female preponderance is approximately 4:1, with most cases (90%) occurring in girls under 2 years of age, leading to intractable VF or cardiac arrest. The lesion resembles a hamartoma with histiocytoid or granular cell features.(400) The condition has clearly been defined as a mitochondrial disorder and affects the function of complexes I and III of the respiratory chain of the cardiac mitochondria.(400) The etiology favors either an autosomal recessive gene or an X-linked condition.

Histopathological findings in patients with histiocytoid cardiomyopathy include multiple flat-to-round, smooth, yellow nodules located beneath the endocardial surface of the left ventricle, the atria, and the four cardiac valves. The nodules are composed of demarcated, large, foamy granular cells. Glycogen, lipids, and pigment may be observed in these cells, as well as a lymphocytic infiltrate. Immunostaining shows perimembranous immunoreactivity for muscle-specific actin, but not for the histiocytic markers, S-100 protein and CD69.(387,391,398,402,403) These cells may be abnormal Purkinje cells; however, a primitive myocardial precursor cannot be excluded. Radiofrequency ablation or pacemaker implantation may be required to treat arrhythmias.(404) Surgical intervention with prolonged survival has been reported.(405)

Shehata et al reported two probands with *de novo* nonsense variants in the X-linked nuclear gene *NDUFB11*, which had not previously been implicated in any disease, despite evidence that deficiency for other mitochondrial electron transport complex I members leads to cardiomyopathy.(406) A third proband was doubly heterozygous for inherited rare variants in additional components of complex I, *NDUFAF2*, and *NDUFB9*, confirming that histiocytoid cardiomyopathy is genetically heterogeneous. In a fourth case, the proband with histiocytoid cardiomyopathy inherited a mitochondrial variant from her heteroplasmic mother, as did her brother, who presented with cardiac arrhythmia. A causal role for *NDUFB11* truncation in the etiology of histiocytoid cardiomyopathy helps explain the disease's female bias. Whereas most complex I deficiencies are thought to be inherited in a Mendelian recessive manner, these two *de novo* variants establish a dominant haploinsufficient phenotype.

Section 5 Other Disorders

5.1 Infiltrative Cardiomyopathies: Amyloidosis

See Evidence Table: ACM Amyloidosis. A recommendation flow diagram is shown in Figure 19.

Cardiac amyloidosis refers to the extracellular deposition of low molecular weight proteins within the myocardium, usually occurring in the context of more widespread organ involvement. The amyloid deposits are typically formed by one of two proteins: light chains or transthyretin.(407,408) Isolated atrial amyloidosis due to atrial natriuretic peptide deposition typically occurs in older age, and small studies have suggested its role in atrial fibrillation.(409,410) Light chain amyloidosis (AL amyloidosis) is secondary to a primary blood dyscrasia, which drives an abnormal proliferation of plasma cells and subsequently the monoclonal overproduction of light chains. Chemotherapy and stem cell transplantation has transformed care and vastly improved survival for AL amyloidosis.(411) Transthyretin amyloid is composed of a different protein, a misfolded prealbumin that will also produce amyloid fibrils and deposits in tissues.(408) Treatment includes liver transplantation, which can retard progression; the results are variable, however, and advanced multiorgan involvement often prevents curing. Newer therapies to stabilize transthyretin, diminish its production, or remove it from affected organs are currently under investigation.(412-416)

Cardiac involvement is in the form of an infiltrative cardiomyopathy in addition to heart failure via primarily diastolic limitation; small vessel disease,(417) conduction system disease,(418-420) and atrial and ventricular arrhythmias(421) are all well recognized. Histological evaluation of hearts with cardiac amyloidosis has provided insight into the potential underlying mechanisms of cardiac arrhythmia. Amyloid fibrils infiltrate the extracellular matrix, disrupting myocardial cellular arrangement and leading to myocardial fibrosis.(422,423) Perivascular amyloid infiltration and impairment of cardiomyocyte function is also well described(424,425), and the subsequent impaired vasoreactivity can result in relative myocardial ischemia and abnormal electrical conduction. This cardiotoxic infiltrative milieu is hypothesized to be the fundamental driver of conduction abnormalities, atrial and ventricular arrhythmias. Although widespread involvement is not uncommon, with sinus node dysfunction well-recognized,(426-428) infranodal conduction system disease appears to be the primary conduction abnormality, as evidenced by HV interval prolongation.(418,429) The disease is associated with the risk of

sudden death in a number of cohorts.(418) Due to the progressive amyloid deposition throughout the heart, sinus node dysfunction and conduction disease often worsen, prompting the consideration for permanent pacemakers. For those patients for whom permanent pacing is necessary, lead placement should be carefully considered, given the potential for further LV depression related to RV pacing dyssynchrony. Currently, there are no studies that can provide definitive guidance on this issue.

Autonomic dysfunction with orthostatic presyncope or syncope is commonly observed in patients with systemic amyloid disease and cardiac involvement, and peripheral vasoconstrictors are frequently needed to manage symptoms.(430-432) A clear conduction abnormality needs to be considered as the etiology in these patients, recognizing that most cases of SCD are likely related to infranodal conduction disease. Furthermore, significant cardiac involvement with advanced infranodal conduction abnormalities can often be masked by a normal-appearing QRS complex.(418,429) By further blocking AV nodal conduction by preventing compensatory physiological heart rate recovery and directly preventing vasoconstriction, the actions of calcium blocking agents converge to create a malignant and potentially lethal combined effect. Evidence is limited, however, to small case series and 2 case reports.(433-435)

The most common tachyarrhythmia in this disorder is atrial arrhythmia. Rate control using AV nodal blocking agents can be especially challenging in the face of the relative hypotension and impairment in compensatory vasoreactivity that is commonly seen with widespread systemic and autonomic impairment. AV nodal ablation has been evaluated and appears to be a reasonable consideration in more resistant and symptomatic cases.(436) Antiarrhythmic approaches are often necessary, given that maintenance of active atrial systole can be imperative for patients with restrictive LV filling; however, extensive amyloid infiltration, when present, could impair atrial systole. Extensive substrate abnormalities, presumably related to extensive atrial amyloid fibril infiltration, are common, and results from atrial fibrillation ablation are less than ideal.(429,436) Frequent ectopy with NSVT is the most common ventricular dysrhythmia, yet neither burden of ectopy nor NSVT appears to predict SCD.(437) Whether ICDs improve survival is not clear(438-442), and progressive heart failure and terminal pulseless electrical activity remains a common theme associated with cardiac death in this group. This situation may be different for patients with cardiac amyloidosis who have been

successfully managed for AL-type disease(421) and for patients awaiting cardiac transplantation; individualized approaches are therefore necessary.

Patients with cardiac amyloidosis remain at high risk for developing intracardiac thrombus and thromboembolic stroke(443,444); anticoagulation needs to be carefully considered even in the absence of atrial arrhythmias.

COR*	LOE	Recommendations	References
I	B-NR	In both symptomatic and asymptomatic individuals with cardiac amyloidosis and second-degree AV block Type II, high-grade AV block or third-degree AV block, a permanent pacemaker is recommended.	(418,426,427,445)
AV block has been consistently linked to sudden death in patients with cardiac amyloidosis; for patients with obvious conduction system abnormalities, pacemaker implantation is recommended.			

COR*	LOE	Recommendations	References
I	C-EO	In individuals with cardiac amyloidosis who have survived a cardiac arrest, an ICD is recommended if meaningful survival greater than 1 year is expected.	
It is not known how many patients in the secondary prevention ICD trials had underlying cardiac amyloidosis. Nevertheless, there is agreement that patients who have been resuscitated following a cardiac arrest are at higher risk of recurrence and can potentially be revived by defibrillation.(3)			

COR*	LOE	Recommendations	References
IIb	B-NR	In individuals with cardiac amyloidosis, the use of digoxin may be considered if used with caution due to the high risk of toxicity.	(446)

Digoxin is known to bind to amyloid fibrils and putatively this action can potentiate its effect on the myocardium. In addition, many patients with cardiac amyloidosis have dysfunction related to the same disease process, and serum digoxin levels can be affected by the reduced excretion. In a cohort of 107 patients with AL amyloidosis who received digoxin, the incidence of significant arrhythmias due to digoxin toxicity was 11%, and 5 patients died.(446)

COR*	LOE	Recommendations	References
IIb	C-EO	In individuals with cardiac amyloidosis and symptomatic atrial arrhythmias, the use of sotalol, dofetilide or amiodarone may be considered.	

Although not studied in a retrospective or prospective manner, atrial arrhythmias are common, often highly symptomatic, and poorly tolerated, mostly due to rapid ventricular rates and irregular ventricular response that impair ventricular filling and contractility. Patients with significant ventricular diastolic disease can also present with symptomatic deterioration in the context of impaired filling without atrial systole, and antiarrhythmic agents are typically required. The class III antiarrhythmics (sotalol, dofetilide, and amiodarone) are mechanistically more suitable for therapy for this patient group, given the preponderance of atrial and ventricular myocardial fibrosis or scarring and the risk of atrial flutter and reentrant ventricular arrhythmia with class Ic agents. The use of class Ic agents can result in persistent atrial flutter in this patient group, which frequently exhibits substrate-related atrial tachycardias.

COR*	LOE	Recommendations	References
IIb	B-NR	In individuals with AL-type cardiac amyloidosis with nonsustained ventricular arrhythmias, a prophylactic ICD may be considered if meaningful survival greater than 1 year is expected.	(421)

Primary prevention ICD implantation remains controversial, and there are conflicting data on the prevention of SCD in cardiac amyloidosis. Potentially curative therapies have emerged to manage certain subtypes,(421) and outcomes for AL amyloidosis could be more favorable in this regard. Patients awaiting heart transplantation are also being considered for disease cure and should likely also be considered independently.

COR*	LOE	Recommendations	References
IIb	C-LD	In individuals with cardiac amyloidosis and symptomatic atrial arrhythmias, cardiac ablation may be considered.	(436)

It is important for clinicians to recognize that ablation for atrial arrhythmias has limited efficacy and high recurrence rates, even when performed in major referral centers. Patients with rapid ventricular rates and those resistant to medical therapy also appear to benefit symptomatically from combined AV nodal ablation and permanent pacemaker implantation. In a cohort of 26 patients, 13 of whom underwent catheter ablation for atrial arrhythmia (atrial fibrillation, atrial flutter, or atrial tachycardia), the 1- and 3-year recurrence-free survival rate was 70% and 60%, respectively. The remaining 13 patients underwent AV node ablation. Both ablation groups had improved symptoms, and 11 patients died during the study period.(436)

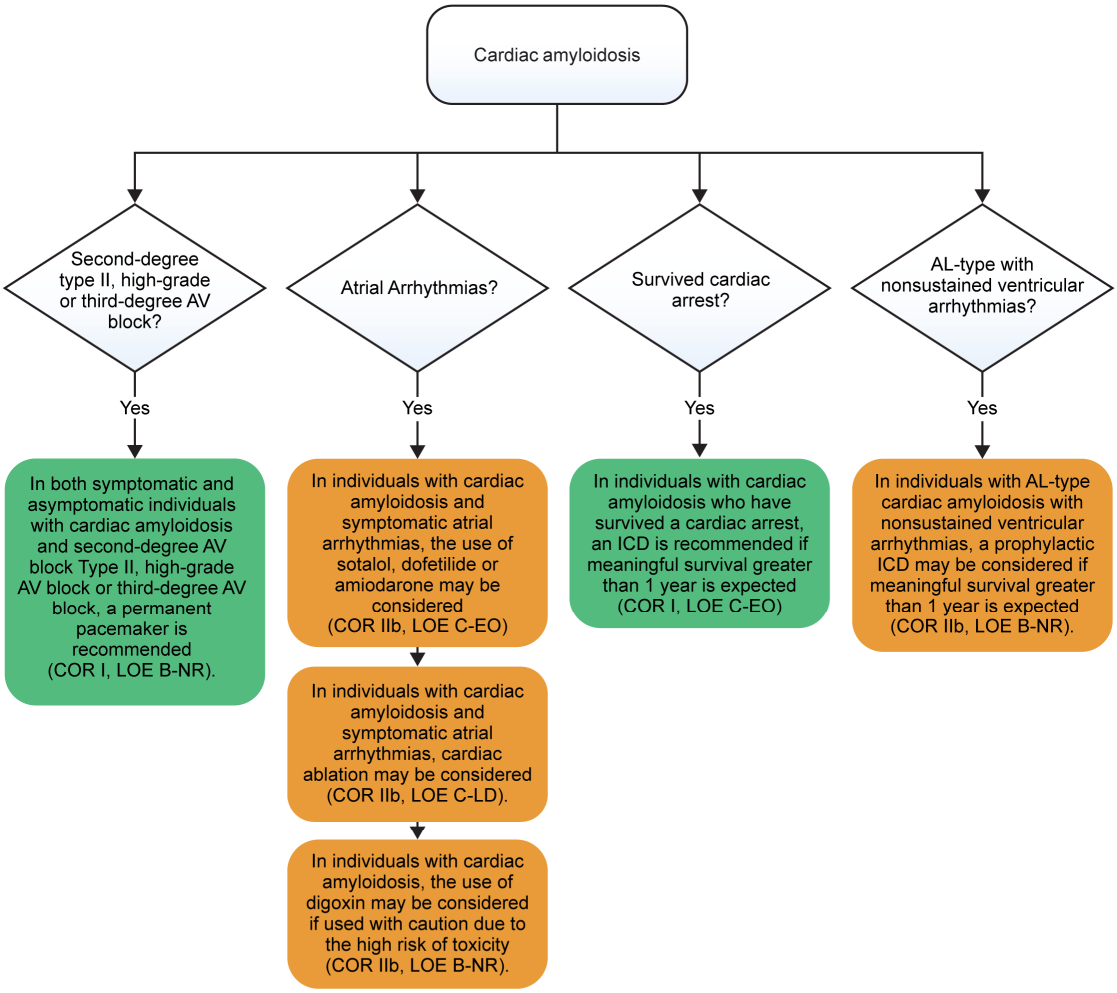


Figure 19. Amyloidosis arrhythmia treatment recommendations. AV=atrioventricular; AL=amyloid light-chain; COR=Class of Recommendation; LOE=Level of Evidence. Colors correspond to COR in Figure 1.

5.2 Brugada Syndrome

Since the initial clinical description of BrS, there has been a search for structural abnormalities in patients with the Brugada phenotype, which has been challenging to prove unequivocally. Simple imaging with transthoracic echocardiography is typically normal for patients with BrS, but the technique clearly lacks the ability to image this relevant heart region (ie, the RVOT area) with meaningful resolution. However, echocardiographic studies have demonstrated delayed activation of the right ventricle, in which the degree of delay correlated well with the degree of

ST-elevation.(447) However, higher-resolution CT and cardiac MRI, have consistently revealed structural abnormalities and enlarged ventricular volumes,(448,449) which could be particularly relevant in patients with *SCN5A*-mediated BrS.(450) The potential contribution of structural abnormalities has taken on renewed interest with the advent of epicardial mapping and ablation(451) and recent preliminary histopathologic data from individuals with the Brugada phenotype and sudden death.(452)

Several groups have performed endomyocardial biopsies of patients with BrS, which have yielded mixed results, from findings of lymphocytic infiltrates to severe fibro-fatty infiltration suggestive of ARVC.(453-455) Frustaci et al examined 18 consecutive symptomatic patients with BrS with endomyocardial biopsy of both ventricles, finding evidence of abnormalities in all patients.(455) Histopathology was subsequently shown to be heterogeneous in a subsequent study in 2008, whereby nonspecific lymphocytic changes in the biopsies of 21 patients with BrS could not be classified into any pathognomonic pattern.(454) In a recent evaluation of 6 postmortem hearts from presumed BrS-related sudden death, epicardial surface, interstitial fibrosis, and reduced GJ expression were observed in the RVOT.(452) Fibrosis and reduced GJ expression colocalized with abnormal potentials from previous epicardial mapping studies. These observations correlate with the previous observation that ablation of epicardial scar potentials attenuates and may even abolish the Brugada phenotype and life-threatening arrhythmias.(451) Abnormal myocardial structure and conduction are therefore likely to be at least partially responsible for the development of the Brugada phenotype.(456)

5.3 Potassium Channels: KCNQ1, KCNH2, and TRMP4

5.3.1 KCNQ1

Xiong et al identified a 60-year-old man who initially presented with episodes of palpitations and was found to have recurrent VT with LBBB morphology on a 12-lead ECG, frequent ventricular ectopy, and runs of NSVT on 24-hour Holter monitoring during the initial evaluation, with no family history of SCD, cardiac arrhythmias, or HF.(457) An echocardiogram showed an enlarged left ventricle with mildly depressed LV systolic function with an ejection fraction of 45%. He had no obstructive coronary lesions in the coronary angiography and subsequently underwent radiofrequency catheter ablation of the VT and ICD implantation and was administered a beta-blocker. Follow-up echocardiograms showed persistent LV dilation and systolic dysfunction and

an LVEF of 42%. A *KCNQ1 p.R397Q* pathologic variant, which was predicted to be disease-related, was identified at the C-terminal domain of the KCNQ1 channel protein. The *KCNQ1-R397Q* variant was located in the C-terminal domain of the α-subunit of the functional KCNQ1 channel complex, which is considered an interacting domain necessary for the assembly of the channels at the membrane.(458) Tail current density and peak tail current density at +70 mV were significantly reduced in cells expressing the mutant protein, and localization of the mutant KCNQ1-R397Q protein to the cell membrane was reduced as compared with the KCNQ1-WT protein, all consistent with loss of function of KCNQ1. Loss-of-function variants in the *KCNQ1* gene are known to cause LQTS type 1 (LQT1), whereas a gain-of-function variant causes sinus bradycardia, familial atrial fibrillation, SQTS, and sudden infant death syndrome.(459-463) A 12-lead ECG in the index case with the *KCNQ1-R397Q* pathogenic variant showed a QTc interval of 480 ms in the presence of a severe intraventricular conduction defect. The clinical phenotype, which is distinct from the classic LQT1, is consistent with the loss-of-function effect of the *KCNQ1-R397Q* variant on trafficking of the KCNQ1 protein to the membrane and decreased I_{Ks} tail current density. The *KCNQ1-R397Q* variant was also identified in a 21-year-old female victim of SCD, whose cardiac autopsy demonstrated myocyte hypertrophy, disarray, fibrosis, and fatty replacement, a phenotype reminiscent of ACM. (464)

In addition, Kharbanda et al presented genetic and phenotypic data from 4 family members across 2 generations with evidence of prolonged QT interval and LVNC in association with a pathogenic variant in *KCNQ1.*(465) The association of LQTS LVNC is uncommon, with only 1 reported case in association with a pathogenic *KCNQ1* variant. In this case, a 5-year-old girl suffered a cardiac arrest and was found to have LVNC and prolonged QTc, and a previously reported pathogenic *KCNQ1* variant (c.1831G > T, D611Y), located in the C-terminus of *KCNQ1*. Several members of her family were found to carry this variant, but none had detected ECG or echocardiographic abnormalities.(466)

5.3.2 KCNH2

Two cases of LQTS and LVNC have also been reported by Ogawa et al, with both patients having different *KCNH2* variants.(467) SCD has occurred in these types of patients but has not been commonly reported. The optimal therapy is unclear at this time, although beta-blocker therapy has been successful in treating *KCNQ1*-and *KCNH2*-associated LQTS. ICD implantation has been

used for patients with this form of LQTS who experienced an episode of sudden cardiac arrest.(465)

5.3.3 TRPM4

The transient receptor potential melastatin 4 (TRPM4) channel mediates a Ca^{2+}-activated nonselective cationic current (I_{NSCca}).(468-470) In the heart, the TRPM4 channel represents the cardiac Ca^{2+}-activated transient inward current (I_{ti}) and plays a key role in the cardiac conduction system. At negative membrane potentials, TRPM4 channels catalyze Na^+ entry into the cell, leading to cellular membrane depolarization. At positive membrane potentials, TRPM4 channels can catalyze cellular K^+ efflux, leading to membrane repolarization. TRPM4 activity can therefore reduce or increase the driving force for Ca^{2+}. The potential influence of TRPM4 on the driving force of Ca^{2+} has an important impact on the frequency of intracellular Ca^{2+} oscillation in T-cells(471) and HL1-mouse cardiomyocytes.(472) Inhibition of TRPM4 channels in these cells abolishes the Ca^{2+} oscillations and leads to a phasic concentration of intracellular Ca^{2+}. TRPM4 is expressed in many cell types but is expressed most abundantly in the heart,(468) where it may participate in intracellular Ca^{2+} sensing and affect cellular excitability by influencing the membrane potential in all cell types. The impact of TRPM4 downregulation or upregulation depends on cell type and the presence of other ion channels, as well as exchangers and transporters.

Dominantly inherited variants in the TRPM4 gene of 4 families were shown to be associated with the cardiac bundle-branch disorder progressive familial heart block type I (PFHB1), isolated cardiac conduction disease (ICCD),(473,474) AV conduction block, RBBB, bradycardia, and BrS.(475,476)

TRPM4 channels carrying PFHB1 and ICCD variants display a dominant gain-of-function phenotype, which is not associated with alterations in biophysical properties but with an increase in TRPM4 current density.(473,474)

Daumy et al(477) reported on the genetic screening of 95 unrelated patients with progressive conduction system disease and identified 13 individuals with pathologic variants in the TRPM4 gene. One variant was found in a 4-generational family; systematic familial screening showed that there were 96 family members, 57 of whom could be recruited and studied. Twelve patients were diagnosed with conduction defects, 6 of whom (50%) underwent pacemaker

implantation. Ten of the 12 patients presented with RBBB, 8 of whom showed left anterior hemiblock. Functional and biochemical analyses demonstrated that this variant, TRPM4-p.I376T, results in increased current density concomitant with augmented TRPM4 channel expression at the cell surface. LVNC was also identified in one of the family members. The affected patients were 34 ± 25 years of age; however, babies, children, and adolescents were affected as well. Almost no information regarding the patient with LVNC was provided, except that she had been diagnosed as a baby with LVNC, RBBB, left anterior hemiblock, and had been implanted a pacemaker.

Using a custom gene panel consisting of 115 genes known to be associated with cardiomyopathic phenotypes and channelopathies, Forleo et al (478) analyzed 38 unrelated patients: 16 with DCM, 14 with HCM, and 8 with ARVC, recruited on the basis of more severe phenotypes and a family history of cardiomyopathy and/or sudden death. In 23 of 38 patients, at least one novel potential gene–phenotype association was identified. In the case of ACM, the authors found 1 patient with asymptomatic DCM and a *N915D-TRPM4* pathologic variant with a family history of sudden death in 3 of 4 affected family members. The authors also identified an *E289K-TRPM4* pathologic variant in a patient who presented with resuscitated cardiac arrest due to VF, an initial ECG with inverted T waves from V1 to V3, and subsequent features of first-degree AV block, NSVT, paroxysmal AF, a 2D echocardiogram demonstrating a dilated right ventricle, and a cardiac MRI that demonstrated dyskinetic areas at the free and inferior walls of the right ventricle. The patient underwent ICD implantation. A *V1185I-TRPM4* pathologic variant was identified in the patient, who also had a family history of sudden death occurring in 3 of 4 affected family members. Therapy in this patient cohort included pacemaker implantation and, in some cases, an ICD.(477)

Saito et al also identified a TRPM4 pathogenic variant in patients with ventricular noncompaction and cardiac conduction disease, thereby further expanding the role of TRPM4 abnormalities in ACM.(479)

Management of cardiomyopathy also needs to be taken into account, using standard therapy.

5.3.4 Phospholamban

Phospholamban, which is encoded by the *PLN* gene, is a transmembrane phosphoprotein of SR and is a key regulator of calcium homeostasis.(129,480) Pathogenic gene variants in *PLN*, mostly

leading to the inhibition of calcium uptake into the SR, can cause genetic forms of cardiomyopathy, particularly those associated with early-onset of rhythm disturbance.(480,481) The pathogenic *PLN R14del* gene variant is commonly identified in patients diagnosed with ACM who have been initially diagnosed with DCM or ARVC.(481,482) In the Netherlands, the *PLN R14del* pathologic variant is a founder variant and has been identified in 10%–15% of patients diagnosed with ACM, either arrhythmogenic DCM or ARVC.(33,483) The phenotype of *PLN R14del* variant carriers, obtained from a limited number of index patients and family members, is characterized by a low-voltage ECG, a high frequency of malignant ventricular arrhythmias, and end-stage heart failure.(33,481,482) Natural history insights into this inherited disorder, including onset, risk stratification for malignant ventricular arrhythmias, mortality, and prevention of SCD, which require large, unselected multicenter cohorts consisting of index patients and relatives, are difficult to identify; however, a number of studies have attempted to do so.(80,161) The yield from screening cardiomyopathy populations for pathologic *PLN* variants is generally very low, ranging from 0.08%-0.38% in selected cohorts.(481,484) The *PLN R14del* pathogenic variant was identified in 13% (31 of 240) of Dutch patients diagnosed with DCM and in 12% (12 of 97) of Dutch patients diagnosed with ARVC.(33) The arrhythmogenic burden of the *PLN R14del* pathogenic variant was demonstrated by the high rate of appropriate ICD discharges and a positive family history of SCD. Additionally, *PLN R14del* pathogenic variant carriers more frequently underwent cardiac transplantation compared with patients with familial DCM.(33) Cascade screening has identified many family members carrying the same pathogenic variants. Variable expression and age-dependent penetrance are characteristics observed with the *PLN R14del* pathogenic variant. Sepehrkhouy et al evaluated the distribution pattern of cardiac fibrosis in hearts with desmosomal vs *PLN R14del* pathogenic variant cardiomyopathy and compared this pattern with fibrosis in other hereditary cardiomyopathies,(485) demonstrating that cardiomyopathies associated with desmosomal or the *PLN R14del* pathogenic variant have a distinct fibrosis pattern. The posterolateral wall of the LV was particularly discriminating, and hearts with the *PLN R14del* pathogenic variant cardiomyopathy showed significantly more fibrosis in the LV free wall than those with pathogenic desmosomal variants. Both desmosomal and *PLN R14del* pathogenic variants were strongly associated with life-threatening ventricular arrhythmias. Patients with pathogenic desmosomal variants had RV fibro-fatty changes and fibrosis with fatty changes in the outer part of the LV wall, predominantly in the posterolateral part, in line with earlier observations in autopsy studies from patients with ACM with unknown

genotypes(486) and in transgenic mouse models of desmosomal ARVC.(487) LV pathology confirmed the LGE studies of cardiac MRI that typically involve the subepicardial and midwall layers of the inferolateral region of the LV in ACM.(488-490) Hearts from patients with a *PLN R14del* pathogenic variant also had a pattern of RV fibro-fatty replacement and LV fibrosis with fatty changes mostly in the posterolateral wall, regardless of clinical presentation.(491,492) However, hearts with the *PLN R14del* pathogenic variants had significantly more fibrosis in the left ventricle and less fat in the right ventricle compared with hearts with desmosomal variants. These patterns were also seen in a cohort of 153 Dutch patients with ACM and in a combined United States and Dutch cohort of 577 patients in which more LV involvement in patients with PLN pathogenic variants was observed than in those with desmosomal pathogenic variants using electrocardiographic and imaging criteria (echocardiography, cardiac MRI, RV/LV cine-angiography).(141,493) The distribution in fibrosis patterns suggested that different variants could make the cardiomyocyte vulnerable todifferent stressors with potential damaging mechanisms that are not evenly distributed over the various regions of the myocardium. The authors speculated that the pattern of predominantly RV and LV (posterolateral) epicardial fibrosis or fibrofatty replacement is induced by increased sensitivity to wall stress on the heart. This is supported by the demonstration that exercise induces a 125% increase in end-systolic wall stress in the right ventricle, compared with only 14% in the left ventricle,(494) suggesting that the right ventricle is more vulnerable to wall stress.

Following the arrhythmogenic profile of the *PLN R14del* pathogenic variant, primary prevention by implanting an ICD could be beneficial for variant carriers.(33,481,482)

5.4 Left Ventricular Noncompaction

See Evidence Table: Left Ventricular Noncompaction. Recommendation flowcharts are shown in Figure 20 and Figure 21.

LVNC is a genetic disorder characterized by excessive and unusual trabeculations within the left ventricle, which is thought to occur due to developmental arrest and failure of the heart to fully form the compact myocardium during the final phase of cardiac development.(495,496) Genetic inheritance arises in at least 30%–50% of patients and is thought to occur at a rate of approximately 1 case per 7000 live births.(497,498) LVNC is characterized by a spongy morphological appearance of the myocardium occurring primarily in the left ventricle, with abnormal trabeculations typically being most evident in the apical, mid-lateral, and inferior

portions of the left ventricle.(499-501) The right ventricle can also be affected, causing RV noncompaction or biventricular noncompaction.(500,502) The LV myocardium comprises 2 distinct layers, a compact and a noncompact layer, along with prominent trabeculae and deep intertrabecular recesses.(495,498) Apical thinning of the compact layer is also typical. These features may be associated with normal ventricular chamber dimensions, wall thickness and function, LV dilation or hypertrophy, systolic and/or diastolic dysfunction, atrial enlargement, various forms of congenital heart disease, or arrhythmias. Noncompaction cardiomyopathy is therefore phenotypically heterogeneous and can be subclassified into 9 different forms, including the most benign form (in which the LV size, thickness, and systolic and diastolic function are normal, with no associated early-onset arrhythmias), an RV form, a biventricular form, a DCM form, an HCM form, an RCM form, a mixed form (combination of HCM and DCM or DCM and RCM), a congenital heart disease form, and an arrhythmogenic form.(11,500) The more severe phenotypes are most typically observed in children, especially those younger than 1 year of age. High-resolution cardiac imaging, such as with CMR, has improved the ability to find the most benign form. Focal LVNC was observed in at least 1 LV myocardial segment in 43% of participants without heart disease or hypertension in a United States population-based cardiac MRI study and in 2 segments in 6% of this cohort.(503) These findings were replicated in a cardiac MRI study from a population cohort from the United Kingdom, in which 14.8% of individuals met at least 1 criterion for LVNC, and 4.4% met the most specific criterion.(504) The myocardium in LVNC can change unexpectedly from one form to another ("undulating phenotype").(505) Although many patients are asymptomatic, LV or RV failure commonly occurs and causes heart failure symptoms, which can be exercise-induced or persistent at rest. Patients undergoing long-term treatment sometimes present acutely with decompensated heart failure. Other life-threatening risks include ventricular arrhythmias and AV block, which can present clinically as syncope or sudden death.(500) Typically, rhythm abnormalities occur early in the presentation in some patients, most commonly being observed at the time of the initial diagnosis, consistent with an ACM. LVNC occurs in newborns, young children, adolescents, and adults, with the worst reported outcomes observed in infants and in those in the third and fourth decades of life. In some families, a consistent LVNC phenotype is observed in affected relatives; quite commonly, however, individuals with features of LVNC are found in families in which other affected relatives have been diagnosed with typical HCM, DCM, RCM, or ACM. Variants in approximately 15 genes have been implicated as causing noncompaction cardiomyopathy and

include genes encoding desmosomal (desmoplakin and plakophilin 2), cytoskeletal, sarcomeric (most common), and ion channel proteins. Disrupted mitochondrial function and metabolic abnormalities also have a causal role.(353,354,506-509) Treatment focuses on improving cardiac efficiency and reducing mechanical stress in those patients with systolic dysfunction. Arrhythmia therapy and ICD implantation to prevent sudden death are the mainstays of treatment when deemed necessary and appropriate.(510) LVNC can be associated with a malignant course in children or adults, and risk stratification is lacking.(500,506,511) Patients with LVNC associated with arrhythmias with or without systolic or diastolic dysfunction should avoid endurance exercise and competitive sports.

5.4.1 Diagnostic Methods and Criteria

5.4.1.1 Noninvasive Imaging

Echocardiography has been the diagnostic imaging technique of first choice, with cardiac MRI (CMR) more recently becoming the diagnostic gold standard. The typical diagnostic criteria for echocardiography and CMR rely mainly on the ratio of the noncompacted layer to the compact layer thickness, evidence of intertrabecular recesses filled from the LV cavity by color Doppler echocardiography, and segmental localization of hypertrabeculation diagnostic of noncompaction. The ability of cardiac MRI to identify the presence and extent of LGE as a surrogate marker of myocardial fibrosis is also employed to determine the extent of LV scarring (which has been significantly related to ECG abnormalities and tachyarrhythmias) and LV dysfunction. In patients with LVNC evaluated by cardiac MRI, the degree of LV trabeculation had no prognostic effect over and above LV dilation, LV systolic dysfunction, and the presence of LGE.(512)

5.4.1.2 Electrocardiography

Normal electrocardiographic results are rare in LVNC, with 80%–90% of ECGs being abnormal. Infants and young children commonly have excessive voltage, predominantly in the anterolateral leads.(513) These individuals, particularly those with early childhood presentation of LVNC, may have associated pre-excitation as well. Arrhythmias (including SVT, VT, and atrial fibrillation/flutter) are common and dangerous accompaniments in LVNC. Conduction system abnormalities also occur. In the systematic review by Bhatia et al,(514) most arrhythmias in patients with LVNC were VT and atrial fibrillation, with the prevalence of VT approaching 40%

and SCD resulting in more than 55% of LVNC-related deaths. Brescia et al(511) reported on the evaluation of 242 children with isolated LVNC and noted that 31 (12.8%) died, 150 (62%) presented with or developed cardiac dysfunction, and 13 (5.4%) underwent transplantation. The presence of cardiac dysfunction was strongly associated with mortality (HR: 11; *P*<.001). ECG abnormalities were observed in 87% of the patients, with ventricular hypertrophy and repolarization abnormalities occurring most commonly. Repolarization abnormalities were associated with increased mortality (HR: 2.1; *P*=.02). Eighty (33.1%) children had an arrhythmia, and those with arrhythmias had increased mortality (HR: 2.8; *P*=.002), with 42 (17.4%) having ventricular tachycardia and 5 presenting with resuscitated SCD. In total, there were 15 cases of SCD in the cohort (6.2%). Nearly all patients who suddenly died (14 of 15) had abnormal cardiac dimensions or cardiac dysfunction and early-onset arrhythmias. The authors concluded that the mortality rate in children with LVNC has a strong association with arrhythmia development, with preceding cardiac dysfunction or ventricular arrhythmias associated with increased mortality. Muser et al studied 9 patients (mean age of 42 ± 15 years) diagnosed with LVNC and ventricular arrhythmias, including 3 with VT and 6 with frequent PVCs despite treatment with a mean of 2 ± 1 antiarrhythmic drugs.(515) The authors conducted EPSs and identified ablation sites using a combination of entrainment, activation, late or fractionated potential ablation, and pace mapping. Eight (89%) patients showed LV systolic dysfunction, with a mean ejection fraction of 40% ± 13%. Patients who presented with VT had evidence of abnormal electroanatomic substrate involving the mid to apical segments of the LV, which matched the noncompacted myocardial segments identified by CMR or echocardiography prior to the procedure. In patients presenting with frequent PVCs, the site of origin was identified at the papillary muscles (50%) and/or the basal septal regions (67%). After a median follow-up of 4 years (range 1–11) and a mean of 1.8 ± 1.1 procedures, ventricular arrhythmias recurred in only 1 patient (11%), and significant improvement in LV function occurred in 50% of cases.

5.4.2 Treatment

According to the ACC/AHA guidelines on device-based therapy for cardiac rhythm abnormalities,(4) there are sufficient observational data to indicate that ICD placement as a strategy to reduce the risk of sudden death can be a reasonable clinical strategy for primary prevention for patients with LVNC.(4) ICD implantation should follow the general guidelines for primary and secondary prevention (4). Patients with LVNC who have a moderate reduction in LV

systolic function are more likely to have a primary prevention indication for ICD placement. Gleva et al evaluated 661 adults with LVNC, a mean age of 46.4 ± 14.9 years (55% male, 45% female), 2/3 having heart failure (30% class III/IV) with a mean LVEF of 33.4 ± 15.5%. Atrial fibrillation/flutter occurred in 21% of patients, while 67% had non-sustained VT, and 30% had VT or prior VT arrest (5%).(516) In 78% of patients, An ICD was placed as primary prevention while 20% required an ICD for secondary prevention.

COR*	LOE	Recommendations	References
I	B-NR	If the proband has a disease-causing gene variant, it is recommended that first-degree relatives of individuals with LVNC undergo clinical screening for the disease along with genetic counseling and genetic testing.	(349,506,515)
IIa	B-NR	In individuals with the clinical diagnosis of pathologic LVNC, genetic counseling and genetic testing is reasonable for diagnosis and for gene-specific targeted cascade family screening.	(349,506)

LVNC is an autosomal dominant inherited disorder, which therefore has a 50% chance of passed on from gene carriers to offspring or first-degree relatives. Genetic testing for individuals with LVNC could identify the causative gene and then allow for gene-specific targeted cascade family screening as a prevention measure that identifies at-risk family members. Variants in approximately 15 genes have been implicated as causative of noncompaction cardiomyopathy and include genes encoding desmosomal (desmoplakin and plakophilin 2), cytoskeletal, sarcomeric (most common), and ion channel proteins. In addition, disrupted mitochondrial function and metabolic abnormalities have a causal role.(353,354,506-509) In a study of 194 relatives of 50 unrelated LVNC probands,(506) 64% showed familial cardiomyopathy that also included HCM and DCM. Due to the substantial overlap of LVNC with other forms of cardiomyopathy, genetic testing panels should encompass genes in which variants are associated with these other forms of cardiomyopathy. Among 17 asymptomatic relatives, 8 carriers had nonpenetrance. In a study of 128 pediatric patients with LVNC (349), 75 of whom underwent genetic testing, the yield was 9%. Furthermore, patients with isolated LVNC were less likely to have a genetic test. Given the genetic heterogeneity and variable

presentation and penetrance of LVNC, family members need a comprehensive approach that includes clinical screening and genetic counseling and testing.

COR*	LOE	Recommendations	References
I	B-NR	ICD implantation is recommended for individuals with LVNC and evidence of ventricular tachyarrhythmias associated with syncope or resuscitated sudden death if meaningful survival greater than 1 year is expected.	(510)
IIa	B-NR	ICD implantation is reasonable for individuals with LVNC and evidence of nonsustained VT associated with a reduced ejection fraction.	(510,511)

Patients with LVNC with evidence of VT associated with syncope or resuscitated sudden death are at high risk. In a cohort of 44 prospectively analyzed patients with LVNC (510) who were implanted with an ICD for either secondary (n=12 for VF or sustained VT) or primary (n=32, for heart failure with severe LV dysfunction) prevention, 8 patients (4 implanted with an ICD for primary prevention and 4 implanted for secondary prevention) received appropriate ICD therapies in a median follow-up time of 6.1 months. Inappropriate ICD therapies occurred in 6 patients implanted with an ICD for primary prevention and in 3 patients implanted for secondary prevention. Complications with ICD implantation can occur regardless of the underlying etiology but are infrequent (estimated at less than 2% in a registry of patients that included those with LVNC).(516)

Among primary prevention patients, those who are at higher risk for adverse arrhythmic outcomes are associated with LV dysfunction. In a cohort of 242 pediatric patients with isolated LVNC,(511) 15 experienced SCD, 15 of whom had abnormal cardiac dimensions or ventricular function, whereas those children with normal function and dimensions were at low risk for sudden death. Of 42 patients with VT, 5 had presented with resuscitated SCD; the mortality risk was also increased for 80 children with an arrhythmia (HR: 2.8; *P*=.002).

COR*	**LOE**	**Recommendations**	**References**
I	B-NR	Anticoagulation is recommended in individuals with LVNC with atrial fibrillation and in those with previous embolic events.	(517)
IIb	B-NR	Anticoagulation may be reasonable in individuals with LVNC with evidence of ventricular dysfunction.	(517)

LVNC has an increased risk of thromboembolism when associated with atrial fibrillation or in individuals with prior embolism. Thrombus formation may occur in the intertrabecular recesses of the left ventricle, leading to the possibility of ejection to the coronary arteries, causing ischemia, or to the brain, resulting in a stroke. In a cohort of 144 patients with LVNC,(517) stroke or peripheral embolism occurred in 22 patients, with 14 identified as due to a cardioembolic cause. A cardioembolic cause for stroke was related to either the presence of atrial fibrillation or systolic dysfunction, This further strengthens the indications for anticoagulation based upon well-established studies of stroke risk in patients with atrial fibrillation.(518) In pediatric patients aspirin is often used.

COR*	LOE	Recommendations	References
IIb	B-NR	In individuals with suspected LVNC, the diagnostic criteria by echocardiography or cardiac MRI, measured as the maximal ratio of noncompaction to compaction (NC/C), may be reasonable for establishing a diagnosis.	(375,512,516,519,520)
IIb	B-NR	In individuals with suspected LVNC and ventricular arrhythmias, cardiac MRI or other advanced cardiac imaging may be reasonable for establishing a diagnosis and for risk stratification.	(512,520,521)

The maximum noncompaction to compaction ratio (NC/C) in the LV has been employed as a diagnostic criterion with mixed results, and its relationship with outcomes is uncertain. In an analysis of 700 patients referred for cardiac MRI,(520) imaging criteria for LVNC were analyzed based on the ratio of noncompacted to compacted myocardium or trabeculation mass. The authors found a wide range for the apparent prevalence of LVNC according to the imaging criteria used and, furthermore, that the clinical outcome of death, ischemic stroke, VT, VF, or heart failure hospitalization was not related to the presence or absence of LVNC by any of the criteria. In a study of 199 patients with LV systolic dysfunction compared with healthy controls,(375) echocardiographic criteria for LVNC, including the ratio of noncompacted to compacted myocardium, were observed in 23.6% of the patients, with 5 control patients (4 of whom were black) meeting the echocardiographic criteria for LVNC despite having no history of cardiovascular disease. These findings raise into question the specificity of echocardiographic

criteria to diagnose LVNC and suggest that trabeculation is the result of increased circulatory volume. This is further supported by a study of pregnant patients, which found that trabeculations are commonly observed during pregnancy, a time of increased LV loading conditions, and that trabeculations regress postpartum.(519)

For patients with suspected LVNC and ventricular arrhythmias, cardiac MRI or other advanced cardiac imaging can help establish a diagnosis and assist in risk stratification due to better visualization of areas of hypertrabeculation. In a study by Sidhu et al, 8 patients with LVNC diagnosed by other methods (clinical, echocardiogram, and conventional MRI) underwent cardiac CT using a 17-segment model. Other patient groups studied included those with nonischemic DCM, severe aortic stenosis, severe aortic regurgitation, HCM, and LV hypertrophy due to hypertension and a control group of 20 patients without cardiovascular disease. The authors found that a ratio of noncompacted to compacted myocardium >2.3 distinguished LVNC, with a sensitivity of 88% and specificity of 97%.

In a study of 113 patients(512) with LVNC determined by echocardiography who underwent cardiac MRI, all demonstrated a ratio of noncompacted to compacted myocardium of at least 2.3 in diastole. Additional MRI criteria were analyzed, including LV dilation, LGE, and percentage of noncompacted myocardial mass (the ratio of noncompacted to compacted mass exceeding 3:1 or 2:1 based upon the segment that was analyzed). Patients were followed for cardiac events for a mean period of 48 ± 24 months. LV dilation, systolic dysfunction, and fibrosis were found to be predictors of cardiac events but not the indices related to noncompacted myocardium. The use of advanced cardiac imaging in patients suspected of LVNC can help establish the diagnosis and possibly provide risk stratification.

The data published in the Multi-Ethnic Study of Atherosclerosis suggests that, using cardiac MRI, a ratio of trabeculated to compact myocardium of >2.3 is common in a large population-based cohort (43% had a ratio >2.3 in at least 1 region). Only 6% of participants in the study had a maximum ratio >2.3 in more than 2 regions in an older age population (mean age of 68 years).(503,522)

See Table 5 for diagnostic criteria for LVNC.

Table 5. Diagnostic criteria for LVNC. C=compaction; CM=compacted myocardium; echo= echocardiogram; LV=left ventricular; MRI=magnetic resonance imaging; NC/C=maximum noncompaction to compaction ratio; NCM=noncompacted myocardium.

References	Modality	N	LVNC Diagnostic Criteria
(523)	Echo	8	2 layers, excessively prominent ventricular trabeculations, progressively increased total myocardial wall thickness from mitral valve and towards the apex, CM/(NCM + CM) ≤ 0.5 at end-diastole (short-axis parasternal and/or apical views)
(524)	Echo	34	2 layers, intertrabecular recesses by CFD, no co-existing structural abnormality, NC/C layer ≥2
(373)	Echo	62	>3 trabeculations protruding from LV wall apically to papillary muscle. End-diastolic NC/C layer ≥2
(498)	MRI	7	2 layers. End-diastolic NC/C>2.3
(525)	MRI	16	Total LV trabeculated mass without papillary muscles. End-diastolic NC layer volume >20%

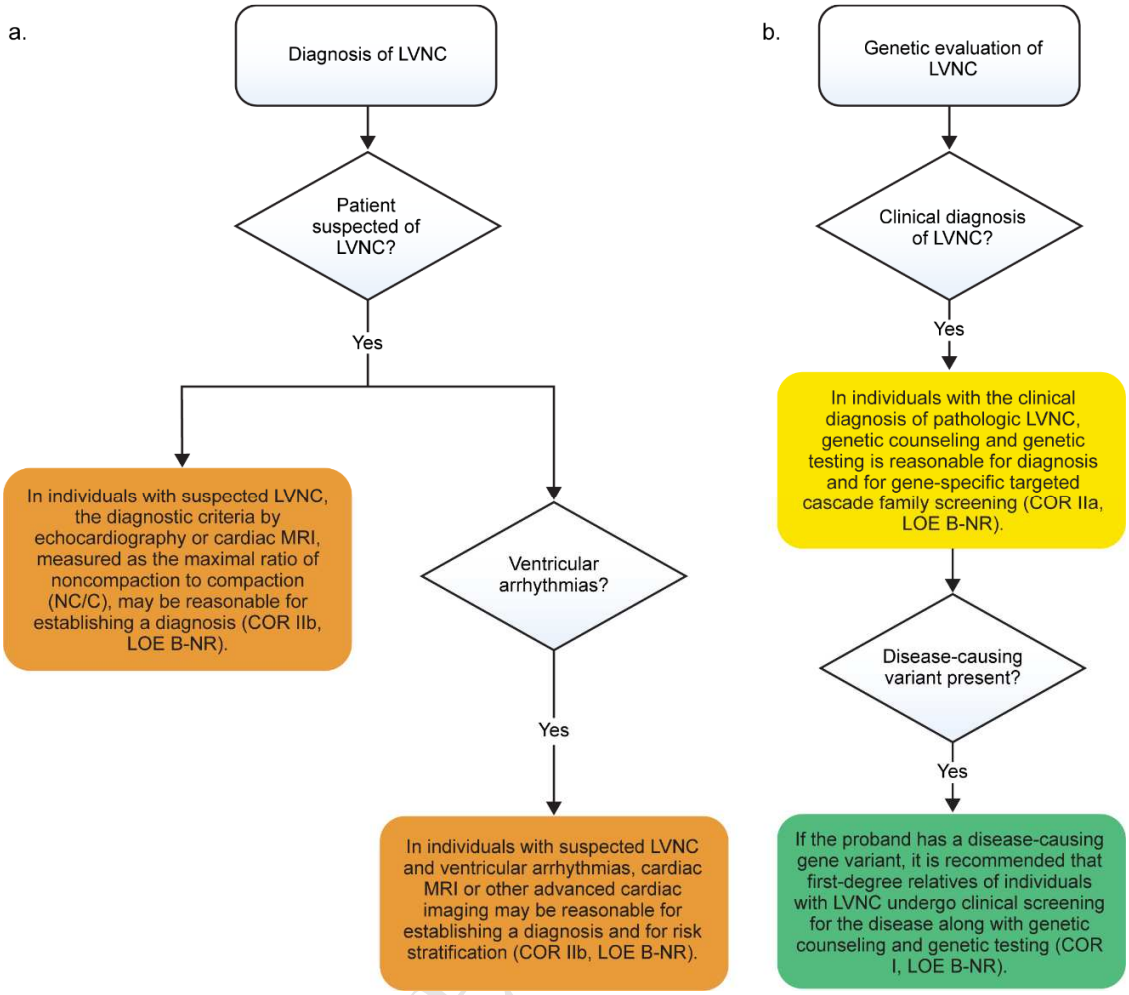


Figure 20. Diagnosis and risk stratification of LVNC (a) and family and genetic evaluation of LVNC (b). COR=Class of Recommendation; LOE=Level of Evidence;LVNC=left ventricular noncompaction. Colors correspond to COR in Figure 1.

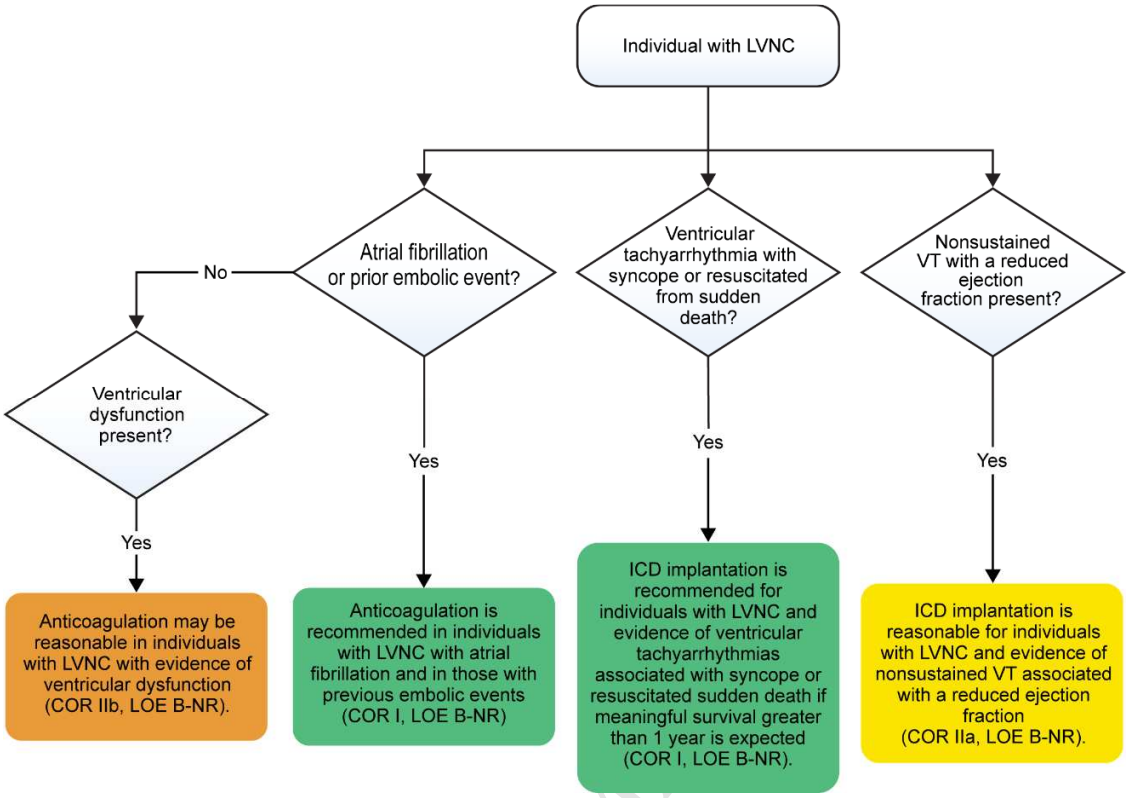


Figure 21. LVNC treatment recommendations. Anticoagulation refers to vitamin K antagonists and direct oral anticoagulants. Children are often administered aspirin. COR=Class of Recommendation; LOE=Level of Evidence; LVNC=left ventricular noncompaction; ICD=implantable cardioverter defibrillator. Colors correspond to Class of Recommendation in Figure 1.

Section 6 Future Directions and Research Recommendations

In the future, a variety of new approaches to the understanding of mechanisms responsible for the development and progression of ACMs will be a key focus. With this knowledge, novel treatment options based on targeting members of final common pathways at the gene and protein level can potentially be designed and tested. Gene editing could also provide novel options, as could regeneration medicine. To achieve these goals, research must focus on the array of disorders categorized under the umbrella of ACMs. Potential topics for study would include the following:

1. Mechanisms of desmosome/ID disruption and cell–cell pulling apart.
2. Mechanisms by which exercise results in early-onset and increase severity of ACM.
3. Mechanisms responsible for generating arrhythmias.

4. Nondesmosomal causes of ACM.
5. Utility of genetic testing in ACM prognosis.
6. Differences between right- and left-sided disease outcomes.
7. Medical therapy approaches.
8. Arrhythmia management approaches.
9. Gene editing and regenerative medicine; scientific methods and studies in animals and humans.

Appendix 1: Author disclosure table

Appendix 2: Peer Reviewer disclosure table

References

1. Indik JH, Patton KK, Beardsall M et al. HRS Clinical Document Development Methodology Manual and Policies: Executive summary. Heart Rhythm 2017;14:e495-e500.
2. Halperin JL, Levine GN, Al-Khatib SM et al. Further Evolution of the ACC/AHA Clinical Practice Guideline Recommendation Classification System: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. Circulation 2016;133:1426-8.
3. Al-Khatib SM, Stevenson WG, Ackerman MJ et al. 2017 AHA/ACC/HRS Guideline for Management of Patients With Ventricular Arrhythmias and the Prevention of Sudden Cardiac Death: Executive Summary: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines and the Heart Rhythm Society. Heart Rhythm 2017.
4. Epstein AE, DiMarco JP, Ellenbogen KA et al. ACC/AHA/HRS 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the ACC/AHA/NASPE 2002 Guideline Update for Implantation of Cardiac Pacemakers and Antiarrhythmia Devices) developed in collaboration with the American Association for Thoracic Surgery and Society of Thoracic Surgeons. J Am Coll Cardiol 2008;51:e1-62.
5. Ackerman MJ, Priori SG, Willems S et al. HRS/EHRA expert consensus statement on the state of genetic testing for the channelopathies and cardiomyopathies this document was developed as a partnership between the Heart Rhythm Society (HRS) and the European Heart Rhythm Association (EHRA). Heart Rhythm 2011;8:1308-39.
6. Priori SG, Wilde AA, Horie M et al. HRS/EHRA/APHRS expert consensus statement on the diagnosis and management of patients with inherited primary arrhythmia syndromes: document endorsed by HRS, EHRA, and APHRS in May 2013 and by ACCF, AHA, PACES, and AEPC in June 2013. Heart Rhythm 2013;10:1932-63.
7. Yancy CW, Jessup M, Bozkurt B et al. 2016 ACC/AHA/HFSA Focused Update on New Pharmacological Therapy for Heart Failure: An Update of the 2013 ACCF/AHA Guideline for the Management of Heart Failure: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines and the Heart Failure Society of America. J Am Coll Cardiol 2016;68:1476-1488.
8. Yancy CW, Jessup M, Bozkurt B et al. 2013 ACCF/AHA guideline for the management of heart failure: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. J Am Coll Cardiol 2013;62:e147-239.
9. Ponikowski P, Voors AA, Anker SD et al. 2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure: The Task Force for the diagnosis and treatment of acute and chronic heart failure of the European Society of Cardiology (ESC)Developed with the special contribution of the Heart Failure Association (HFA) of the ESC. European heart journal 2016;37:2129-200.
10. Marcus FI, McKenna WJ, Sherrill D et al. Diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia: proposed modification of the task force criteria. Circulation 2010;121:1533–41.
11. Hershberger RE, Givertz MM, Ho CY et al. Genetic Evaluation of Cardiomyopathy-A Heart Failure Society of America Practice Guideline. Journal of cardiac failure 2018;24:281-302.

12. Corrado D, Wichter T, Link MS et al. Treatment of Arrhythmogenic Right Ventricular Cardiomyopathy/Dysplasia: An International Task Force Consensus Statement. Circulation 2015;132:441–53.
13. McKenna WJ, Stewart JT, Nihoyannopoulos P, McGinty F, Davies MJ. Hypertrophic cardiomyopathy without hypertrophy: two families with myocardial disarray in the absence of increased myocardial mass. British heart journal 1990;63:287-90.
14. Watkins H, Ashrafian H, Redwood C. Inherited cardiomyopathies. N Engl J Med 2011;364:1643-56.
15. Mogensen J, Kubo T, Duque M et al. Idiopathic restrictive cardiomyopathy is part of the clinical expression of cardiac troponin I mutations. The Journal of clinical investigation 2003;111:209-16.
16. Dalla Volta S, Battaglia G, Zerbini E. "Auricularization' of right ventricular pressure curve. Am Heart J 1961;61:25-33.
17. Marcus FI, Fontaine GH, Guiraudon G et al. Right ventricular dysplasia: a report of 24 adult cases. Circulation 1982;65:384-98.
18. Rowland E, McKenna WJ, Sugrue D, Barclay R, Foale RA, Krikler DM. Ventricular tachycardia of left bundle branch block configuration in patients with isolated right ventricular dilatation. Clinical and electrophysiological features. British heart journal 1984;51:15-24.
19. McKenna WJ, Thiene G, Nava A et al. Diagnosis of arrhythmogenic right ventricular dysplasia/cardiomyopathy. Task Force of the Working Group Myocardial and Pericardial Disease of the European Society of Cardiology and of the Scientific Council on Cardiomyopathies of the International Society and Federation of Cardiology. British heart journal 1994;71:215–8.
20. Coonar AS, Protonotarios N, Tsatsopoulou A et al. Gene for arrhythmogenic right ventricular cardiomyopathy with diffuse nonepidermolytic palmoplantar keratoderma and woolly hair (Naxos disease) maps to 17q21. Circulation 1998;97:2049–58.
21. Protonotarios A, Anastasakis A, Panagiotakos DB et al. Arrhythmic risk assessment in genotyped families with arrhythmogenic right ventricular cardiomyopathy. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2016;18:610-6.
22. McKoy G, Protonotarios N, Crosby A et al. Identification of a deletion in plakoglobin in arrhythmogenic right ventricular cardiomyopathy with palmoplantar keratoderma and woolly hair (Naxos disease). Lancet 2000;355:2119-24.
23. Norgett EE, Hatsell SJ, Carvajal-Huerta L et al. Recessive mutation in desmoplakin disrupts desmoplakin-intermediate filament interactions and causes dilated cardiomyopathy, woolly hair and keratoderma. Hum Mol Genet 2000;9:2761-6.
24. Gerull B, Heuser A, Wichter T et al. Mutations in the desmosomal protein plakophilin-2 are common in arrhythmogenic right ventricular cardiomyopathy. Nature genetics 2004;36:1162-4.
25. Syrris P, Ward D, Asimaki A et al. Desmoglein-2 mutations in arrhythmogenic right ventricular cardiomyopathy: a genotype-phenotype characterization of familial disease. European heart journal 2007;28:581-8.
26. Syrris P, Ward D, Evans A et al. Arrhythmogenic right ventricular dysplasia/cardiomyopathy associated with mutations in the desmosomal gene desmocollin-2. American journal of human genetics 2006;79:978-84.

27. Vatta M, Marcus F, Towbin JA. Arrhythmogenic right ventricular cardiomyopathy: a 'final common pathway' that defines clinical phenotype. European heart journal 2007;28:529-30.
28. Towbin JA, Lorts A. Arrhythmias and dilated cardiomyopathy common pathogenetic pathways? J Am Coll Cardiol 2011;57:2169-71.
29. Towbin JA. Desmosomal gene variants in patients with "possible ARVC". Heart Rhythm 2011;8:719-20.
30. Sen-Chowdhry S, Prasad SK, Syrris P et al. Cardiovascular magnetic resonance in arrhythmogenic right ventricular cardiomyopathy revisited: comparison with task force criteria and genotype. J Am Coll Cardiol 2006;48:2132–40.
31. Norman M, Simpson M, Mogensen J et al. Novel mutation in desmoplakin causes arrhythmogenic left ventricular cardiomyopathy. Circulation 2005;112:636–42.
32. Kumar S, Baldinger SH, Gandjbakhch E et al. Long-Term Arrhythmic and Nonarrhythmic Outcomes of Lamin A/C Mutation Carriers. J Am Coll Cardiol 2016;68:2299-2307.
33. van der Zwaag PA, van Rijsingen IA, Asimaki A et al. Phospholamban R14del mutation in patients diagnosed with dilated cardiomyopathy or arrhythmogenic right ventricular cardiomyopathy: evidence supporting the concept of arrhythmogenic cardiomyopathy. Eur J Heart Fail 2012;14:1199-207.
34. Ortiz-Genga MF, Cuenca S, Dal Ferro M et al. Truncating FLNC mutations are associated with high-risk dilated and arrhythmogenic cardiomyopathies. J Am Coll Cardiol 2016;68:2440–2451.
35. Bowles NE, Bowles KR, Towbin JA. The "final common pathway" hypothesis and inherited cardiovascular disease. The role of cytoskeletal proteins in dilated cardiomyopathy. Herz 2000;25:168-75.
36. Towbin JA. The role of cytoskeletal proteins in cardiomyopathies. Current opinion in cell biology 1998;10:131-9.
37. Towbin JA, Bowles KR, Bowles NE. Etiologies of cardiomyopathy and heart failure. Nature medicine 1999;5:266-7.
38. Hoshijima M. Mechanical stress-strain sensors embedded in cardiac cytoskeleton: Z disk, titin, and associated structures. American journal of physiology Heart and circulatory physiology 2006;290:H1313-25.
39. Corrado D, Link MS, Calkins H. Arrhythmogenic Right Ventricular Cardiomyopathy. N Engl J Med 2017;376:1489–90.
40. Niroomand F, Carbucicchio C, Tondo C et al. Electrophysiological characteristics and outcome in patients with idiopathic right ventricular arrhythmia compared with arrhythmogenic right ventricular dysplasia. Heart 2002;87:41–7.
41. Towbin JA. Arrhythmogenic right ventricular cardiomyopathy: a paradigm of overlapping disorders. Ann Noninvasive Electrocardiol 2008;13:325-6.
42. Wilmot I, Morales DL, Price JF et al. Effectiveness of mechanical circulatory support in children with acute fulminant and persistent myocarditis. Journal of cardiac failure 2011;17:487-94.
43. Pedersen CT, Kay GN, Kalman J et al. EHRA/HRS/APHRS expert consensus on ventricular arrhythmias. Heart Rhythm 2014;11:e166-96.
44. Steinmetz M, Krause U, Lauerer P et al. Diagnosing ARVC in Pediatric Patients Applying the Revised Task Force Criteria: Importance of Imaging, 12-Lead ECG, and Genetics. Pediatric cardiology 2018;39:1156-1164.

45. Deshpande SR, Herman HK, Quigley PC et al. Arrhythmogenic Right Ventricular Cardiomyopathy/Dysplasia (ARVC/D): Review of 16 Pediatric Cases and a Proposal of Modified Pediatric Criteria. Pediatric cardiology 2016;37:646-55.
46. Chatterjee D, Fatah M, Akdis D et al. An autoantibody identifies arrhythmogenic right ventricular cardiomyopathy and participates in its pathogenesis. European heart journal 2018;39:3932-3944.
47. Calkins H. A new diagnostic test for arrhythmogenic right ventricular cardiomyopathy: is this too good to be true? European heart journal 2018;39:3945-3946.
48. Cox MG, van der Smagt JJ, Noorman M et al. Arrhythmogenic right ventricular dysplasia/cardiomyopathy diagnostic task force criteria: impact of new task force criteria. Circ Arrhythm Electrophysiol 2010;3:126-33.
49. Jaoude SA, Leclercq JF, Coumel P. Progressive ECG changes in arrhythmogenic right ventricular disease. Evidence for an evolving disease. European heart journal 1996;17:1717-22.
50. Nava A, Bauce B, Basso C et al. Clinical profile and long-term follow-up of 37 families with arrhythmogenic right ventricular cardiomyopathy. J Am Coll Cardiol 2000;36:2226–33.
51. Te Riele AS, James CA, Bhonsale A et al. Malignant arrhythmogenic right ventricular dysplasia/cardiomyopathy with a normal 12-lead electrocardiogram: a rare but underrecognized clinical entity. Heart Rhythm 2013;10:1484-91.
52. Mast TP, James CA, Calkins H et al. Evaluation of Structural Progression in Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy. JAMA Cardiol 2017;2:293–302.
53. Piccini JP, Nasir K, Bomma C et al. Electrocardiographic findings over time in arrhythmogenic right ventricular dysplasia/cardiomyopathy. Am J Cardiol 2005;96:122–6.
54. Quarta G, Ward D, Tome Esteban MT et al. Dynamic electrocardiographic changes in patients with arrhythmogenic right ventricular cardiomyopathy. Heart 2010;96:516–22.
55. Cox MG, Nelen MR, Wilde AA et al. Activation delay and VT parameters in arrhythmogenic right ventricular dysplasia/cardiomyopathy: toward improvement of diagnostic ECG criteria. Journal of cardiovascular electrophysiology 2008;19:775-81.
56. Marcus FI, Zareba W. The electrocardiogram in right ventricular cardiomyopathy/dysplasia. How can the electrocardiogram assist in understanding the pathologic and functional changes of the heart in this disease? J Electrocardiol 2009;42:136 e1-5.
57. Peters S, Trummel M. Diagnosis of arrhythmogenic right ventricular dysplasia-cardiomyopathy: value of standard ECG revisited. Ann Noninvasive Electrocardiol 2003;8:238-45.
58. Lohrmann GM, Peters F, Srivathsan K, Essop MR, Mookadam F. Electrocardiographic Abnormalities in Disease-Free Black South Africans and Correlations With Echocardiographic Indexes and Early Repolarization. Am J Cardiol 2016;118:765-70.
59. Malhotra A, Dhutia H, Gati S et al. Anterior T-Wave Inversion in Young White Athletes and Nonathletes: Prevalence and Significance. J Am Coll Cardiol 2017;69:1-9.
60. Marcus FI. Prevalence of T-wave inversion beyond V1 in young normal individuals and usefulness for the diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia. Am J Cardiol 2005;95:1070-1.
61. Jain R, Dalal D, Daly A et al. Electrocardiographic features of arrhythmogenic right ventricular dysplasia. Circulation 2009;120:477-87.

62. Platonov PG, Calkins H, Hauer RN et al. High interobserver variability in the assessment of epsilon waves: Implications for diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia. Heart Rhythm 2016;13:208-16.
63. Tanawuttiwat T, Te Riele AS, Philips B et al. Electroanatomic Correlates of Depolarization Abnormalities in Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy. Journal of cardiovascular electrophysiology 2016;27:443-52.
64. Marcus FI. Epsilon Waves Aid in the Prognosis and Risk Stratification of Patients With ARVC/D. Journal of cardiovascular electrophysiology 2015;26:1211-1212.
65. Protonotarios A, Anastasakis A, Tsatsopoulou A et al. Clinical Significance of Epsilon Waves in Arrhythmogenic Cardiomyopathy. Journal of cardiovascular electrophysiology 2015;26:1204-1210.
66. Cox MG, van der Smagt JJ, Wilde AA et al. New ECG criteria in arrhythmogenic right ventricular dysplasia/cardiomyopathy. Circ Arrhythm Electrophysiol 2009;2:524-30.
67. Nasir K, Bomma C, Tandri H et al. Electrocardiographic features of arrhythmogenic right ventricular dysplasia/cardiomyopathy according to disease severity: a need to broaden diagnostic criteria. Circulation 2004;110:1527-34.
68. Cox MG, van der Zwaag PA, van der Werf C et al. Arrhythmogenic right ventricular dysplasia/cardiomyopathy: pathogenic desmosome mutations in index-patients predict outcome of family screening: Dutch arrhythmogenic right ventricular dysplasia/cardiomyopathy genotype-phenotype follow-up study. Circulation 2011;123:2690-700.
69. Nunes de Alencar Neto J, Baranchuk A, Bayes-Genis A, Bayes de Luna A. Arrhythmogenic right ventricular dysplasia/cardiomyopathy: an electrocardiogram-based review. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2018;20:f3-f12.
70. Nery PB, Beanlands RS, Nair GM et al. Atrioventricular block as the initial manifestation of cardiac sarcoidosis in middle-aged adults. Journal of cardiovascular electrophysiology 2014;25:875-881.
71. Andrade JP, Marin Neto JA, Paola AA et al. I Latin American Guidelines for the diagnosis and treatment of Chagas' heart disease: executive summary. Arquivos brasileiros de cardiologia 2011;96:434-42.
72. Bastiaenen R, Pantazis A, Gonna H et al. The ventricular ectopic QRS interval (VEQSI): Diagnosis of arrhythmogenic right ventricular cardiomyopathy in patients with incomplete disease expression. Heart Rhythm 2016;13:1504–12.
73. Camm CF, Tichnell C, James CA et al. Premature ventricular contraction variability in arrhythmogenic right ventricular dysplasia/cardiomyopathy. Journal of cardiovascular electrophysiology 2015;26:53–7.
74. Kamath GS, Zareba W, Delaney J et al. Value of the signal-averaged electrocardiogram in arrhythmogenic right ventricular cardiomyopathy/dysplasia. Heart Rhythm 2011;8:256–62.
75. Bauce B, Rampazzo A, Basso C et al. Clinical phenotype and diagnosis of arrhythmogenic right ventricular cardiomyopathy in pediatric patients carrying desmosomal gene mutations. Heart Rhythm 2011;8:1686–95.
76. Manyari DE, Duff HJ, Kostuk WJ et al. Usefulness of noninvasive studies for diagnosis of right ventricular dysplasia. Am J Cardiol 1986;57:1147-53.

77. Reant P, Hauer AD, Castelletti S et al. Epicardial myocardial strain abnormalities may identify the earliest stages of arrhythmogenic cardiomyopathy. Int J Cardiovasc Imaging 2016;32:593-601.
78. Haugaa KH, Basso C, Badano LP et al. Comprehensive multi-modality imaging approach in arrhythmogenic cardiomyopathy-an expert consensus document of the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging 2017;18:237-253.
79. Kaplan SR, Gard JJ, Protonotarios N et al. Remodeling of myocyte gap junctions in arrhythmogenic right ventricular cardiomyopathy due to a deletion in plakoglobin (Naxos disease). Heart Rhythm 2004;1:3–11.
80. Sen-Chowdhry S, Syrris P, Ward D, Asimaki A, Sevdalis E, McKenna WJ. Clinical and genetic characterization of families with arrhythmogenic right ventricular dysplasia/cardiomyopathy provides novel insights into patterns of disease expression. Circulation 2007;115:1710–20.
81. Blusztein DI, Zentner D, Thompson T et al. Arrhythmogenic Right Ventricular Cardiomyopathy: A Review of Living and Deceased Probands. Heart, lung & circulation 2018.
82. Corrado D, Calkins H, Link MS et al. Prophylactic implantable defibrillator in patients with arrhythmogenic right ventricular cardiomyopathy/dysplasia and no prior ventricular fibrillation or sustained ventricular tachycardia. Circulation 2010;122:1144–52.
83. Corrado D, Leoni L, Link MS et al. Implantable cardioverter-defibrillator therapy for prevention of sudden death in patients with arrhythmogenic right ventricular cardiomyopathy/dysplasia. Circulation 2003;108:3084–91.
84. Denis A, Sacher F, Derval N et al. Diagnostic value of isoproterenol testing in arrhythmogenic right ventricular cardiomyopathy. Circ Arrhythm Electrophysiol 2014;7:590-7.
85. Angelini A, Basso C, Nava A, Thiene G. Endomyocardial biopsy in arrhythmogenic right ventricular cardiomyopathy. Am Heart J 1996;132:203–6.
86. Basso C, Ronco F, Marcus F et al. Quantitative assessment of endomyocardial biopsy in arrhythmogenic right ventricular cardiomyopathy/dysplasia: an in vitro validation of diagnostic criteria. European heart journal 2008;29:2760–71.
87. Avella A, d'Amati G, Pappalardo A et al. Diagnostic value of endomyocardial biopsy guided by electroanatomic voltage mapping in arrhythmogenic right ventricular cardiomyopathy/dysplasia. Journal of cardiovascular electrophysiology 2008;19:1127–34.
88. Paul M, Stypmann J, Gerss J et al. Safety of endomyocardial biopsy in patients with arrhythmogenic right ventricular cardiomyopathy: a study analyzing 161 diagnostic procedures. JACC Cardiovasc Interv 2011;4:1142–8.
89. Ermakov S, Ursell PC, Johnson CJ et al. Plakoglobin immunolocalization as a diagnostic test for arrhythmogenic right ventricular cardiomyopathy. Pacing Clin Electrophysiol 2014;37:1708–16.
90. Munkholm J, Christensen AH, Svendsen JH, Andersen CB. Usefulness of immunostaining for plakoglobin as a diagnostic marker of arrhythmogenic right ventricular cardiomyopathy. Am J Cardiol 2012;109:272–5.
91. Asimaki A, Tandri H, Huang H et al. A new diagnostic test for arrhythmogenic right ventricular cardiomyopathy. N Engl J Med 2009;360:1075–84.
92. Xu T, Yang Z, Vatta M et al. Compound and digenic heterozygosity contributes to arrhythmogenic right ventricular cardiomyopathy. J Am Coll Cardiol 2010;55:587-97.

93. Sikkema-Raddatz B, Johansson LF, de Boer EN et al. Targeted next-generation sequencing can replace Sanger sequencing in clinical diagnostics. Hum Mutat 2013;34:1035-42.
94. Kapplinger JD, Landstrom AP, Salisbury BA et al. Distinguishing arrhythmogenic right ventricular cardiomyopathy/dysplasia-associated mutations from background genetic noise. J Am Coll Cardiol 2011;57:2317-27.
95. Richards S, Aziz N, Bale S et al. Standards and guidelines for the interpretation of sequence variants: a joint consensus recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology. Genet Med 2015;17:405-24.
96. Plon SE, Eccles DM, Easton D et al. Sequence variant classification and reporting: recommendations for improving the interpretation of cancer susceptibility genetic test results. Hum Mutat 2008;29:1282-91.
97. Van Driest SL, Wells QS, Stallings S et al. Association of Arrhythmia-Related Genetic Variants With Phenotypes Documented in Electronic Medical Records. JAMA 2016;315:47-57.
98. Amendola LM, Dorschner MO, Robertson PD et al. Actionable exomic incidental findings in 6503 participants: challenges of variant classification. Genome Res 2015;25:305-15.
99. Amendola LM, Jarvik GP, Leo MC et al. Performance of ACMG-AMP Variant-Interpretation Guidelines among Nine Laboratories in the Clinical Sequencing Exploratory Research Consortium. American journal of human genetics 2016;99:247.
100. Walsh R, Thomson KL, Ware JS et al. Reassessment of Mendelian gene pathogenicity using 7,855 cardiomyopathy cases and 60,706 reference samples. Genet Med 2017;19:192-203.
101. Manrai AK, Funke BH, Rehm HL et al. Genetic Misdiagnoses and the Potential for Health Disparities. N Engl J Med 2016;375:655-65.
102. De Bortoli M, Beffagna G, Bauce B et al. The p.A897KfsX4 frameshift variation in desmocollin-2 is not a causative mutation in arrhythmogenic right ventricular cardiomyopathy. Eur J Hum Genet 2010;18:776-82.
103. Posch MG, Posch MJ, Perrot A, Dietz R, Ozcelik C. Variations in DSG2: V56M, V158G and V920G are not pathogenic for arrhythmogenic right ventricular dysplasia/cardiomyopathy. Nat Clin Pract Cardiovasc Med 2008;5:E1.
104. Christensen AH, Benn M, Tybjaerg-Hansen A, Haunso S, Svendsen JH. Missense variants in plakophilin-2 in arrhythmogenic right ventricular cardiomyopathy patients--disease-causing or innocent bystanders? Cardiology 2010;115:148-54.
105. Gandjbakhch E, Charron P, Fressart V et al. Plakophilin 2A is the dominant isoform in human heart tissue: consequences for the genetic screening of arrhythmogenic right ventricular cardiomyopathy. Heart 2011;97:844-9.
106. Andreasen C, Nielsen JB, Refsgaard L et al. New population-based exome data are questioning the pathogenicity of previously cardiomyopathy-associated genetic variants. Eur J Hum Genet 2013;21:918-28.
107. Mogensen J, van Tintelen JP, Fokstuen S et al. The current role of next-generation DNA sequencing in routine care of patients with hereditary cardiovascular conditions: a viewpoint paper of the European Society of Cardiology working group on myocardial and pericardial diseases and members of the European Society of Human Genetics. European heart journal 2015;36:1367-70.
108. Rehm HL, Berg JS, Brooks LD et al. ClinGen--the Clinical Genome Resource. N Engl J Med 2015;372:2235-42.

109. Kelly MA, Caleshu C, Morales A et al. Adaptation and validation of the ACMG/AMP variant classification framework for MYH7-associated inherited cardiomyopathies: recommendations by ClinGen's Inherited Cardiomyopathy Expert Panel. Genet Med 2018;20:351-359.
110. Milko LV, Funke BH, Hershberger RE et al. Development of Clinical Domain Working Groups for the Clinical Genome Resource (ClinGen): lessons learned and plans for the future. Genet Med 2018.
111. Ingles J, Goldstein J, Thaxton C et al. Evaluating the Clinical Validity of Hypertrophic Cardiomyopathy Genes. Circ Genom Precis Med 2019;12:e002460.
112. Bienengraeber M, Olson TM, Selivanov VA et al. ABCC9 mutations identified in human dilated cardiomyopathy disrupt catalytic KATP channel gating. Nature genetics 2004;36:382-7.
113. Rampazzo A, Nava A, Malacrida S et al. Mutation in human desmoplakin domain binding to plakoglobin causes a dominant form of arrhythmogenic right ventricular cardiomyopathy. American journal of human genetics 2002;71:1200-6.
114. Taylor M, Graw S, Sinagra G et al. Genetic variation in titin in arrhythmogenic right ventricular cardiomyopathy-overlap syndromes. Circulation 2011;124:876-85.
115. van Hengel J, Calore M, Bauce B et al. Mutations in the area composita protein alphaT-catenin are associated with arrhythmogenic right ventricular cardiomyopathy. European heart journal 2013;34:201–10.
116. Murray B, Hoorntje ET, Te Riele A et al. Identification of sarcomeric variants in probands with a clinical diagnosis of arrhythmogenic right ventricular cardiomyopathy (ARVC). Journal of cardiovascular electrophysiology 2018.
117. Medeiros-Domingo A, Saguner AM, Magyar I et al. Arrhythmogenic right ventricular cardiomyopathy: implications of next-generation sequencing in appropriate diagnosis. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2017;19:1063-1069.
118. Mayosi BM, Fish M, Shaboodien G et al. Identification of Cadherin 2 (CDH2) Mutations in Arrhythmogenic Right Ventricular Cardiomyopathy. Circ Cardiovasc Genet 2017;10.
119. Turkowski KL, Tester DJ, Bos JM, Haugaa KH, Ackerman MJ. Whole exome sequencing with genomic triangulation implicates CDH2-encoded N-cadherin as a novel pathogenic substrate for arrhythmogenic cardiomyopathy. Congenit Heart Dis 2017;12:226-235.
120. De Bortoli M, Postma AV, Poloni G et al. Whole-Exome Sequencing Identifies Pathogenic Variants in TJP1 Gene Associated With Arrhythmogenic Cardiomyopathy. Circ Genom Precis Med 2018;11:e002123.
121. Norton N, Li D, Rieder MJ et al. Genome-wide studies of copy number variation and exome sequencing identify rare variants in BAG3 as a cause of dilated cardiomyopathy. American journal of human genetics 2011;88:273-82.
122. Hedberg C, Melberg A, Kuhl A, Jenne D, Oldfors A. Autosomal dominant myofibrillar myopathy with arrhythmogenic right ventricular cardiomyopathy 7 is caused by a DES mutation. Eur J Hum Genet 2012;20:984-5.
123. Awad MM, Dalal D, Cho E et al. DSG2 mutations contribute to arrhythmogenic right ventricular dysplasia/cardiomyopathy. American journal of human genetics 2006;79:136-42.
124. Yang Z, Bowles NE, Scherer SE et al. Desmosomal dysfunction due to mutations in desmoplakin causes arrhythmogenic right ventricular dysplasia/cardiomyopathy. Circ Res 2006;99:646-55.

125. Asimaki A, Syrris P, Wichter T, Matthias P, Saffitz JE, McKenna WJ. A novel dominant mutation in plakoglobin causes arrhythmogenic right ventricular cardiomyopathy. American journal of human genetics 2007;81:964-73.
126. Vatta M, Mohapatra B, Jimenez S et al. Mutations in Cypher/ZASP in patients with dilated cardiomyopathy and left ventricular non-compaction. J Am Coll Cardiol 2003;42:2014-27.
127. Quarta G, Syrris P, Ashworth M et al. Mutations in the Lamin A/C gene mimic arrhythmogenic right ventricular cardiomyopathy. European heart journal 2012;33:1128-36.
128. Pashmforoush M, Lu JT, Chen H et al. Nkx2-5 pathways and congenital heart disease; loss of ventricular myocyte lineage specification leads to progressive cardiomyopathy and complete heart block. Cell 2004;117:373-86.
129. Schmitt JP, Kamisago M, Asahi M et al. Dilated cardiomyopathy and heart failure caused by a mutation in phospholamban. Science 2003;299:1410-3.
130. Brauch KM, Karst ML, Herron KJ et al. Mutations in ribonucleic acid binding protein gene cause familial dilated cardiomyopathy. J Am Coll Cardiol 2009;54:930-41.
131. McNair WP, Ku L, Taylor MR et al. SCN5A mutation associated with dilated cardiomyopathy, conduction disorder, and arrhythmia. Circulation 2004;110:2163-7.
132. Merner ND, Hodgkinson KA, Haywood AF et al. Arrhythmogenic right ventricular cardiomyopathy type 5 is a fully penetrant, lethal arrhythmic disorder caused by a missense mutation in the TMEM43 gene. American journal of human genetics 2008;82:809-21.
133. Pilichou K, Lazzarini E, Rigato I et al. Large Genomic Rearrangements of Desmosomal Genes in Italian Arrhythmogenic Cardiomyopathy Patients. Circ Arrhythm Electrophysiol 2017;10.
134. Roberts JD, Herkert JC, Rutberg J et al. Detection of genomic deletions of PKP2 in arrhythmogenic right ventricular cardiomyopathy. Clin Genet 2013;83:452–6.
135. Judge DP, Johnson NM. Genetic evaluation of familial cardiomyopathy. Journal of cardiovascular translational research 2008;1:144-54.
136. Baudhuin LM, Leduc C, Train LJ et al. Technical Advances for the Clinical Genomic Evaluation of Sudden Cardiac Death: Verification of Next-Generation Sequencing Panels for Hereditary Cardiovascular Conditions Using Formalin-Fixed Paraffin-Embedded Tissues and Dried Blood Spots. Circ Cardiovasc Genet 2017;10.
137. Carturan E, Tester DJ, Brost BC, Basso C, Thiene G, Ackerman MJ. Postmortem genetic testing for conventional autopsy-negative sudden unexplained death: an evaluation of different DNA extraction protocols and the feasibility of mutational analysis from archival paraffin-embedded heart tissue. Am J Clin Pathol 2008;129:391-7.
138. Bagnall RD, Weintraub RG, Ingles J et al. A Prospective Study of Sudden Cardiac Death among Children and Young Adults. N Engl J Med 2016;374:2441-52.
139. Judge DP. Use of genetics in the clinical evaluation of cardiomyopathy. Jama 2009;302:2471-6.
140. Lopez-Ayala JM, Gomez-Milanes I, Sanchez Munoz JJ et al. Desmoplakin truncations and arrhythmogenic left ventricular cardiomyopathy: characterizing a phenotype. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2014;16:1838-46.

141. Bhonsale A, Groeneweg JA, James CA et al. Impact of genotype on clinical course in arrhythmogenic right ventricular dysplasia/cardiomyopathy-associated mutation carriers. European heart journal 2015;36:847–55.
142. Rigato I, Bauce B, Rampazzo A et al. Compound and digenic heterozygosity predicts lifetime arrhythmic outcome and sudden cardiac death in desmosomal gene-related arrhythmogenic right ventricular cardiomyopathy. Circ Cardiovasc Genet 2013;6:533–42.
143. Fressart V, Duthoit G, Donal E et al. Desmosomal gene analysis in arrhythmogenic right ventricular dysplasia/cardiomyopathy: spectrum of mutations and clinical impact in practice. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2010;12:861-8.
144. Bao J, Wang J, Yao Y et al. Correlation of ventricular arrhythmias with genotype in arrhythmogenic right ventricular cardiomyopathy. Circ Cardiovasc Genet 2013;6:552-6.
145. Groeneweg JA, Bhonsale A, James CA et al. Clinical Presentation, Long-Term Follow-Up, and Outcomes of 1001 Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy Patients and Family Members. Circ Cardiovasc Genet 2015;8:437–46.
146. Te Riele AS, James CA, Groeneweg JA et al. Approach to family screening in arrhythmogenic right ventricular dysplasia/cardiomyopathy. European heart journal 2016;37:755–63.
147. Quarta G, Muir A, Pantazis A et al. Familial evaluation in arrhythmogenic right ventricular cardiomyopathy: impact of genetics and revised task force criteria. Circulation 2011;123:2701-9.
148. Perrin MJ, Angaran P, Laksman Z et al. Exercise testing in asymptomatic gene carriers exposes a latent electrical substrate of arrhythmogenic right ventricular cardiomyopathy. J Am Coll Cardiol 2013;62:1772–9.
149. Pasotti M, Klersy C, Pilotto A et al. Long-term outcome and risk stratification in dilated cardiolaminopathies. J Am Coll Cardiol 2008;52:1250-60.
150. van Rijsingen IA, Nannenberg EA, Arbustini E et al. Gender-specific differences in major cardiac events and mortality in lamin A/C mutation carriers. Eur J Heart Fail 2013;15:376-84.
151. Forleo C, Carmosino M, Resta N et al. Clinical and functional characterization of a novel mutation in lamin a/c gene in a multigenerational family with arrhythmogenic cardiac laminopathy. PLoS One 2015;10:e0121723.
152. Kato K, Takahashi N, Fujii Y et al. LMNA cardiomyopathy detected in Japanese arrhythmogenic right ventricular cardiomyopathy cohort. J Cardiol 2016;68:346-51.
153. Liang JJ, Grogan M, Ackerman MJ. LMNA-Mediated Arrhythmogenic Right Ventricular Cardiomyopathy and Charcot-Marie-Tooth Type 2B1: A Patient-Discovered Unifying Diagnosis. Journal of cardiovascular electrophysiology 2016;27:868-71.
154. Valtuille L, Paterson I, Kim DH, Mullen J, Sergi C, Oudit GY. A case of lamin A/C mutation cardiomyopathy with overlap features of ARVC: a critical role of genetic testing. Int J Cardiol 2013;168:4325-7.
155. Nishiuchi S, Makiyama T, Aiba T et al. Gene-Based Risk Stratification for Cardiac Disorders in LMNA Mutation Carriers. Circ Cardiovasc Genet 2017;10.
156. van Rijsingen IA, Arbustini E, Elliott PM et al. Risk factors for malignant ventricular arrhythmias in lamin a/c mutation carriers a European cohort study. J Am Coll Cardiol 2012;59:493-500.

157. Meune C, Van Berlo JH, Anselme F, Bonne G, Pinto YM, Duboc D. Primary prevention of sudden death in patients with lamin A/C gene mutations. N Engl J Med 2006;354:209-10.
158. Lopez-Ayala JM, Ortiz-Genga M, Gomez-Milanes I et al. A mutation in the Z-line Cypher/ZASP protein is associated with arrhythmogenic right ventricular cardiomyopathy. Clin Genet 2015;88:172-6.
159. Milting H, Klauke B, Christensen AH et al. The TMEM43 Newfoundland mutation p.S358L causing ARVC-5 was imported from Europe and increases the stiffness of the cell nucleus. European heart journal 2015;36:872-81.
160. Hodgkinson KA, Connors SP, Merner N et al. The natural history of a genetic subtype of arrhythmogenic right ventricular cardiomyopathy caused by a p.S358L mutation in TMEM43. Clin Genet 2013;83:321–31.
161. van Rijsingen IA, van der Zwaag PA, Groeneweg JA et al. Outcome in phospholamban R14del carriers: results of a large multicentre cohort study. Circ Cardiovasc Genet 2014;7:455–65.
162. Kalia SS, Adelman K, Bale SJ et al. Recommendations for reporting of secondary findings in clinical exome and genome sequencing, 2016 update (ACMG SF v2.0): a policy statement of the American College of Medical Genetics and Genomics. Genet Med 2017;19:249-255.
163. Haggerty CM, James CA, Calkins H et al. Electronic health record phenotype in subjects with genetic variants associated with arrhythmogenic right ventricular cardiomyopathy: a study of 30,716 subjects with exome sequencing. Genet Med 2017;19:1245-1252.
164. Ashley EA, Hershberger RE, Caleshu C et al. Genetics and cardiovascular disease: a policy statement from the American Heart Association. Circulation 2012;126:142-57.
165. Morales A, Cowan J, Dagua J, Hershberger RE. Family history: an essential tool for cardiovascular genetic medicine. Congestive heart failure (Greenwich, Conn) 2008;14:37-45.
166. Ingles J, Yeates L, Semsarian C. The emerging role of the cardiac genetic counselor. Heart Rhythm 2011;8:1958-62.
167. Waddell-Smith KE, Donoghue T, Oates S et al. Inpatient detection of cardiac-inherited disease: the impact of improving family history taking. Open heart 2016;3:e000329.
168. Dunn KE, Caleshu C, Cirino AL, Ho CY, Ashley EA. A clinical approach to inherited hypertrophy: the use of family history in diagnosis, risk assessment, and management. Circ Cardiovasc Genet 2013;6:118-31.
169. van Tintelen JP, Van Gelder IC, Asimaki A et al. Severe cardiac phenotype with right ventricular predominance in a large cohort of patients with a single missense mutation in the DES gene. Heart Rhythm 2009;6:1574–83.
170. Hasselberg NE, Haland TF, Saberniak J et al. Lamin A/C cardiomyopathy: young onset, high penetrance, and frequent need for heart transplantation. European heart journal 2018;39:853-860.
171. Te Riele A, James CA, Sawant AC et al. Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy in the Pediatric Population: Clinical Characterization and Comparison With Adult-Onset Disease. JACC Clin Electrophysiol 2015;1:551-560.
172. Dalal D, James C, Devanagondi R et al. Penetrance of mutations in plakophilin-2 among families with arrhythmogenic right ventricular dysplasia/cardiomyopathy. J Am Coll Cardiol 2006;48:1416–24.

173. Hamid MS, Norman M, Quraishi A et al. Prospective evaluation of relatives for familial arrhythmogenic right ventricular cardiomyopathy/dysplasia reveals a need to broaden diagnostic criteria. J Am Coll Cardiol 2002;40:1445–50.
174. te Riele AS, James CA, Rastegar N et al. Yield of serial evaluation in at-risk family members of patients with ARVD/C. J Am Coll Cardiol 2014;64:293-301.
175. Mast TP, Teske AJ, Walmsley J et al. Right Ventricular Imaging and Computer Simulation for Electromechanical Substrate Characterization in Arrhythmogenic Right Ventricular Cardiomyopathy. J Am Coll Cardiol 2016;68:2185–2197.
176. Ackerman JP, Bartos DC, Kapplinger JD, Tester DJ, Delisle BP, Ackerman MJ. The Promise and Peril of Precision Medicine: Phenotyping Still Matters Most. Mayo Clin Proc 2016.
177. Cadrin-Tourigny J, Bosman LP, Nozza A et al. A new prediction model for ventricular arrhythmias in arrhythmogenic right ventricular cardiomyopathy. European heart journal 2019.
178. Hulot JS, Jouven X, Empana JP, Frank R, Fontaine G. Natural history and risk stratification of arrhythmogenic right ventricular dysplasia/cardiomyopathy. Circulation 2004;110:1879–84.
179. Link MS, Laidlaw D, Polonsky B et al. Ventricular arrhythmias in the North American multidisciplinary study of ARVC: predictors, characteristics, and treatment. J Am Coll Cardiol 2014;64:119–25.
180. Orgeron GM, James CA, Te Riele A et al. Implantable Cardioverter-Defibrillator Therapy in Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy: Predictors of Appropriate Therapy, Outcomes, and Complications. J Am Heart Assoc 2017;6.
181. Hodgkinson KA, Parfrey PS, Bassett AS et al. The impact of implantable cardioverter-defibrillator therapy on survival in autosomal-dominant arrhythmogenic right ventricular cardiomyopathy (ARVD5). J Am Coll Cardiol 2005;45:400-8.
182. Bardy GH, Lee KL, Mark DB et al. Amiodarone or an implantable cardioverter-defibrillator for congestive heart failure. N Engl J Med 2005;352:225-37.
183. Mazzanti A, Ng K, Faragli A et al. Arrhythmogenic Right Ventricular Cardiomyopathy: Clinical Course and Predictors of Arrhythmic Risk. J Am Coll Cardiol 2016;68:2540–2550.
184. Pinamonti B, Dragos AM, Pyxaras SA et al. Prognostic predictors in arrhythmogenic right ventricular cardiomyopathy: results from a 10-year registry. European heart journal 2011;32:1105-13.
185. Bansch D, Antz M, Boczor S et al. Primary prevention of sudden cardiac death in idiopathic dilated cardiomyopathy: the Cardiomyopathy Trial (CAT). Circulation 2002;105:1453-8.
186. Desai AS, Fang JC, Maisel WH, Baughman KL. Implantable defibrillators for the prevention of mortality in patients with nonischemic cardiomyopathy: a meta-analysis of randomized controlled trials. JAMA 2004;292:2874-9.
187. Kadish A, Dyer A, Daubert JP et al. Prophylactic defibrillator implantation in patients with nonischemic dilated cardiomyopathy. N Engl J Med 2004;350:2151-8.
188. Strickberger SA, Hummel JD, Bartlett TG et al. Amiodarone versus implantable cardioverter-defibrillator:randomized trial in patients with nonischemic dilated cardiomyopathy and asymptomatic nonsustained ventricular tachycardia--AMIOVIRT. J Am Coll Cardiol 2003;41:1707-12.
189. Anselme F, Moubarak G, Savoure A et al. Implantable cardioverter-defibrillators in lamin A/C mutation carriers with cardiac conduction disorders. Heart Rhythm 2013;10:1492-8.

190. Kimura Y, Noda T, Otsuka Y et al. Potentially Lethal Ventricular Arrhythmias and Heart Failure in Arrhythmogenic Right Ventricular Cardiomyopathy: What Are the Differences Between Men and Women? JACC Clin Electrophysiol 2016;2:546-555.
191. Bristow MR, Saxon LA, Boehmer J et al. Cardiac-resynchronization therapy with or without an implantable defibrillator in advanced chronic heart failure. N Engl J Med 2004;350:2140-50.
192. Zannad F, Gattis Stough W, Rossignol P et al. Mineralocorticoid receptor antagonists for heart failure with reduced ejection fraction: integrating evidence into clinical practice. European heart journal 2012;33:2782-95.
193. McMurray JJ, Packer M, Desai AS et al. Angiotensin-neprilysin inhibition versus enalapril in heart failure. N Engl J Med 2014;371:993-1004.
194. Swedberg K, Komajda M, Bohm M et al. Ivabradine and outcomes in chronic heart failure (SHIFT): a randomised placebo-controlled study. Lancet 2010;376:875-85.
195. Abdul-Rahim AH, Shen L, Rush CJ, Jhund PS, Lees KR, McMurray JJV. Effect of digoxin in patients with heart failure and mid-range (borderline) left ventricular ejection fraction. Eur J Heart Fail 2018;20:1139-1145.
196. Tracy CM, Epstein AE, Darbar D et al. 2012 ACCF/AHA/HRS focused update of the 2008 guidelines for device-based therapy of cardiac rhythm abnormalities: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines and the Heart Rhythm Society. [corrected]. Circulation 2012;126:1784-800.
197. Fabritz L, Hoogendijk MG, Scicluna BP et al. Load-reducing therapy prevents development of arrhythmogenic right ventricular cardiomyopathy in plakoglobin-deficient mice. J Am Coll Cardiol 2011;57:740-50.
198. Wlodarska EK, Wozniak O, Konka M, Rydlewska-Sadowska W, Biederman A, Hoffman P. Thromboembolic complications in patients with arrhythmogenic right ventricular dysplasia/cardiomyopathy. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2006;8:596-600.
199. Homma S, Thompson JL, Pullicino PM et al. Warfarin and aspirin in patients with heart failure and sinus rhythm. N Engl J Med 2012;366:1859-69.
200. Lip GY, Ponikowski P, Andreotti F et al. Thrombo-embolism and antithrombotic therapy for heart failure in sinus rhythm. A joint consensus document from the ESC Heart Failure Association and the ESC Working Group on Thrombosis. Eur J Heart Fail 2012;14:681-95.
201. January CT, Wann LS, Alpert JS et al. 2014 AHA/ACC/HRS guideline for the management of patients with atrial fibrillation: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and the Heart Rhythm Society. J Am Coll Cardiol 2014;64:e1-76.
202. Kirchhof P, Benussi S, Kotecha D et al. 2016 ESC Guidelines for the management of atrial fibrillation developed in collaboration with EACTS. European heart journal 2016;37:2893-2962.
203. Ruwald MH, Abu-Zeitone A, Jons C et al. Impact of carvedilol and metoprolol on inappropriate implantable cardioverter-defibrillator therapy: the MADIT-CRT trial (Multicenter Automatic Defibrillator Implantation With Cardiac Resynchronization Therapy). J Am Coll Cardiol 2013;62:1343-50.
204. Moss AJ, Schuger C, Beck CA et al. Reduction in inappropriate therapy and mortality through ICD programming. N Engl J Med 2012;367:2275-83.

205. Gasparini M, Proclemer A, Klersy C et al. Effect of long-detection interval vs standard-detection interval for implantable cardioverter-defibrillators on antitachycardia pacing and shock delivery: the ADVANCE III randomized clinical trial. Jama 2013;309:1903-11.
206. Saeed M, Hanna I, Robotis D et al. Programming implantable cardioverter-defibrillators in patients with primary prevention indication to prolong time to first shock: results from the PROVIDE study. Journal of cardiovascular electrophysiology 2014;25:52-9.
207. Marcus GM, Glidden DV, Polonsky B et al. Efficacy of antiarrhythmic drugs in arrhythmogenic right ventricular cardiomyopathy: a report from the North American ARVC Registry. J Am Coll Cardiol 2009;54:609-15.
208. Connolly SJ, Dorian P, Roberts RS et al. Comparison of beta-blockers, amiodarone plus beta-blockers, or sotalol for prevention of shocks from implantable cardioverter defibrillators: the OPTIC Study: a randomized trial. Jama 2006;295:165-71.
209. Ermakov S, Gerstenfeld EP, Svetlichnaya Y, Scheinman MM. Use of flecainide in combination antiarrhythmic therapy in patients with arrhythmogenic right ventricular cardiomyopathy. Heart Rhythm 2017;14:564-569.
210. Kannankeril PJ, Moore JP, Cerrone M et al. Efficacy of Flecainide in the Treatment of Catecholaminergic Polymorphic Ventricular Tachycardia: A Randomized Clinical Trial. JAMA Cardiol 2017;2:759-766.
211. Salvage SC, Chandrasekharan KH, Jeevaratnam K et al. Multiple targets for flecainide action: implications for cardiac arrhythmogenesis. British journal of pharmacology 2018;175:1260-1278.
212. Tokuda M, Tedrow UB, Kojodjojo P et al. Catheter ablation of ventricular tachycardia in nonischemic heart disease. Circ Arrhythm Electrophysiol 2012;5:992-1000.
213. Sapp JL, Wells GA, Parkash R et al. Ventricular Tachycardia Ablation versus Escalation of Antiarrhythmic Drugs. N Engl J Med 2016;375:111-21.
214. Tung R, Vaseghi M, Frankel DS et al. Freedom from recurrent ventricular tachycardia after catheter ablation is associated with improved survival in patients with structural heart disease: An International VT Ablation Center Collaborative Group study. Heart Rhythm 2015;12:1997-2007.
215. Tzou WS, Tung R, Frankel DS et al. Outcomes after repeat ablation of ventricular tachycardia in structural heart disease: An analysis from the International VT Ablation Center Collaborative Group. Heart Rhythm 2017;14:991-997.
216. Santangeli P, Zado ES, Supple GE et al. Long-Term Outcome With Catheter Ablation of Ventricular Tachycardia in Patients With Arrhythmogenic Right Ventricular Cardiomyopathy. Circ Arrhythm Electrophysiol 2015;8:1413-21.
217. Mallidi J, Nadkarni GN, Berger RD, Calkins H, Nazarian S. Meta-analysis of catheter ablation as an adjunct to medical therapy for treatment of ventricular tachycardia in patients with structural heart disease. Heart Rhythm 2011;8:503-10.
218. Philips B, te Riele AS, Sawant A et al. Outcomes and ventricular tachycardia recurrence characteristics after epicardial ablation of ventricular tachycardia in arrhythmogenic right ventricular dysplasia/cardiomyopathy. Heart Rhythm 2015;12:716-25.
219. Bai R, Di Biase L, Shivkumar K et al. Ablation of ventricular arrhythmias in arrhythmogenic right ventricular dysplasia/cardiomyopathy: arrhythmia-free survival after endo-epicardial substrate based mapping and ablation. Circ Arrhythm Electrophysiol 2011;4:478-85.
220. Berruezo A, Acosta J, Fernandez-Armenta J et al. Safety, long-term outcomes and predictors of recurrence after first-line combined endoepicardial ventricular tachycardia substrate ablation in arrhythmogenic cardiomyopathy. Impact of arrhythmic substrate

distribution pattern. A prospective multicentre study. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2017;19:607-616.

221. Dalal D, Jain R, Tandri H et al. Long-term efficacy of catheter ablation of ventricular tachycardia in patients with arrhythmogenic right ventricular dysplasia/cardiomyopathy. J Am Coll Cardiol 2007;50:432-40.
222. Garcia FC, Bazan V, Zado ES, Ren JF, Marchlinski FE. Epicardial substrate and outcome with epicardial ablation of ventricular tachycardia in arrhythmogenic right ventricular cardiomyopathy/dysplasia. Circulation 2009;120:366-75.
223. Reddy VY, Reynolds MR, Neuzil P et al. Prophylactic catheter ablation for the prevention of defibrillator therapy. N Engl J Med 2007;357:2657-65.
224. Marchlinski FE, Haffajee CI, Beshai JF et al. Long-Term Success of Irrigated Radiofrequency Catheter Ablation of Sustained Ventricular Tachycardia: Post-Approval THERMOCOOL VT Trial. J Am Coll Cardiol 2016;67:674-683.
225. Stevenson WG, Wilber DJ, Natale A et al. Irrigated radiofrequency catheter ablation guided by electroanatomic mapping for recurrent ventricular tachycardia after myocardial infarction: the multicenter thermocool ventricular tachycardia ablation trial. Circulation 2008;118:2773-82.
226. Zeppenfeld K, Stevenson WG. Ablation of ventricular tachycardia in patients with structural heart disease. Pacing Clin Electrophysiol 2008;31:358-74.
227. Stevenson WG, Soejima K. Catheter ablation for ventricular tachycardia. Circulation 2007;115:2750-60.
228. Soejima K, Stevenson WG, Sapp JL, Selwyn AP, Couper G, Epstein LM. Endocardial and epicardial radiofrequency ablation of ventricular tachycardia associated with dilated cardiomyopathy: the importance of low-voltage scars. J Am Coll Cardiol 2004;43:1834-42.
229. Calkins H, Epstein A, Packer D et al. Catheter ablation of ventricular tachycardia in patients with structural heart disease using cooled radiofrequency energy: results of a prospective multicenter study. Cooled RF Multi Center Investigators Group. J Am Coll Cardiol 2000;35:1905-14.
230. Kumar S, Androulakis AF, Sellal JM et al. Multicenter Experience With Catheter Ablation for Ventricular Tachycardia in Lamin A/C Cardiomyopathy. Circ Arrhythm Electrophysiol 2016;9.
231. Honarbakhsh S, Suman-Horduna I, Mantziari L, Ernst S. Successful Right Ventricular Tachycardia Ablation in a Patient with Left Ventricular Non-compaction Cardiomyopathy. Indian Pacing Electrophysiol J 2013;13:181-4.
232. Jackson N, King B, Viswanathan K, Downar E, Spears D. Case report: Ablation of diffuse inter-trabecular substrate in a patient with isolated ventricular non-compaction. Indian Pacing Electrophysiol J 2015;15:162-4.
233. Chung FP, Lin YJ, Kuo L, Chen SA. Catheter Ablation of Ventricular Tachycardia/Fibrillation in a Patient with Right Ventricular Amyloidosis with Initial Manifestations Mimicking Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy. Korean Circ J 2017;47:282-285.
234. Mlcochova H, Saliba WI, Burkhardt DJ et al. Catheter ablation of ventricular fibrillation storm in patients with infiltrative amyloidosis of the heart. Journal of cardiovascular electrophysiology 2006;17:426-30.

235. Magage S, Linhart A, Bultas J et al. Fabry disease: percutaneous transluminal septal myocardial ablation markedly improved symptomatic left ventricular hypertrophy and outflow tract obstruction in a classically affected male. Echocardiography 2005;22:333-9.
236. Berruezo A, Acosta J, Fernandez-Armenta J. Epicardial ablation may not be necessary in all patients with arrhythmogenic right ventricular dysplasia/cardiomyopathy and frequent ventricular tachycardia: author's reply. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2017;19:2047-2048.
237. Philips B, Madhavan S, James C et al. Outcomes of catheter ablation of ventricular tachycardia in arrhythmogenic right ventricular dysplasia/cardiomyopathy. Circ Arrhythm Electrophysiol 2012;5:499-505.
238. Fontaine G. Arrhythmogenic right ventricular dysplasia. Curr Opin Cardiol 1995;10:16-20.
239. Thiene G, Nava A, Corrado D, Rossi L, Pennelli N. Right ventricular cardiomyopathy and sudden death in young people. N Engl J Med 1988;318:129-33.
240. Corrado D, Basso C, Rizzoli G, Schiavon M, Thiene G. Does sports activity enhance the risk of sudden death in adolescents and young adults? J Am Coll Cardiol 2003;42:1959-63.
241. Corrado D, Basso C, Pavei A, Michieli P, Schiavon M, Thiene G. Trends in sudden cardiovascular death in young competitive athletes after implementation of a preparticipation screening program. JAMA 2006;296:1593-601.
242. Chelko SP, Asimaki A, Andersen P et al. Central role for GSK3beta in the pathogenesis of arrhythmogenic cardiomyopathy. JCI insight 2016;1.
243. Kirchhof P, Fabritz L, Zwiener M et al. Age- and training-dependent development of arrhythmogenic right ventricular cardiomyopathy in heterozygous plakoglobin-deficient mice. Circulation 2006;114:1799-806.
244. Martherus R, Jain R, Takagi K et al. Accelerated cardiac remodeling in desmoplakin transgenic mice in response to endurance exercise is associated with perturbed Wnt/beta-catenin signaling. American journal of physiology Heart and circulatory physiology 2016;310:H174-87.
245. Cerrone M, Montnach J, Lin X et al. Plakophilin-2 is required for transcription of genes that control calcium cycling and cardiac rhythm. Nature communications 2017;8:106.
246. Cruz FM, Sanz-Rosa D, Roche-Molina M et al. Exercise triggers ARVC phenotype in mice expressing a disease-causing mutated version of human plakophilin-2. J Am Coll Cardiol 2015;65:1438-50.
247. Strath SJ, Kaminsky LA, Ainsworth BE et al. Guide to the assessment of physical activity: Clinical and research applications: a scientific statement from the American Heart Association. Circulation 2013;128:2259-79.
248. Levine BD, Baggish AL, Kovacs RJ, Link MS, Maron MS, Mitchell JH. Eligibility and Disqualification Recommendations for Competitive Athletes With Cardiovascular Abnormalities: Task Force 1: Classification of Sports: Dynamic, Static, and Impact: A Scientific Statement From the American Heart Association and American College of Cardiology. Circulation 2015;132:e262-6.
249. Maron BJ, Zipes DP, Kovacs RJ. Eligibility and Disqualification Recommendations for Competitive Athletes With Cardiovascular Abnormalities: Preamble, Principles, and

General Considerations: A Scientific Statement From the American Heart Association and American College of Cardiology. Circulation 2015;132:e256-61.
250. Haskell WL, Lee IM, Pate RR et al. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. Medicine and science in sports and exercise 2007;39:1423-34.
251. Garber CE, Blissmer B, Deschenes MR et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Medicine and science in sports and exercise 2011;43:1334-59.
252. Ainsworth BE, Haskell WL, Herrmann SD et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. Medicine and science in sports and exercise 2011;43:1575-81.
253. James CA, Bhonsale A, Tichnell C et al. Exercise increases age-related penetrance and arrhythmic risk in arrhythmogenic right ventricular dysplasia/cardiomyopathy-associated desmosomal mutation carriers. J Am Coll Cardiol 2013;62:1290-1297.
254. Sawant AC, Te Riele AS, Tichnell C et al. Safety of American Heart Association-recommended minimum exercise for desmosomal mutation carriers. Heart Rhythm 2016;13:199-207.
255. Saberniak J, Hasselberg NE, Borgquist R et al. Vigorous physical activity impairs myocardial function in patients with arrhythmogenic right ventricular cardiomyopathy and in mutation positive family members. Eur J Heart Fail 2014;16:1337-44.
256. Sawant AC, Bhonsale A, te Riele AS et al. Exercise has a disproportionate role in the pathogenesis of arrhythmogenic right ventricular dysplasia/cardiomyopathy in patients without desmosomal mutations. J Am Heart Assoc 2014;3:e001471.
257. La Gerche A, Robberecht C, Kuiperi C et al. Lower than expected desmosomal gene mutation prevalence in endurance athletes with complex ventricular arrhythmias of right ventricular origin. Heart 2010;96:1268-74.
258. Ruwald AC, Marcus F, Estes NA, 3rd et al. Association of competitive and recreational sport participation with cardiac events in patients with arrhythmogenic right ventricular cardiomyopathy: results from the North American multidisciplinary study of arrhythmogenic right ventricular cardiomyopathy. European heart journal 2015;36:1735-43.
259. Lie OH, Dejgaard LA, Saberniak J et al. Harmful Effects of Exercise Intensity and Exercise Duration in Patients With Arrhythmogenic Cardiomyopathy. JACC Clin Electrophysiol 2018;4:744-753.
260. Gupta R, Tichnell C, Murray B et al. Comparison of Features of Fatal Versus Nonfatal Cardiac Arrest in Patients With Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy. Am J Cardiol 2017;120:111-117.
261. Corrado D, Basso C, Thiene G et al. Spectrum of clinicopathologic manifestations of arrhythmogenic right ventricular cardiomyopathy/dysplasia: a multicenter study. J Am Coll Cardiol 1997;30:1512-20.
262. Wang W, Cadrin-Tourigny J, Bhonsale A et al. Arrhythmic outcome of arrhythmogenic right ventricular cardiomyopathy patients without implantable defibrillators. Journal of cardiovascular electrophysiology 2018.
263. Agullo-Pascual E, Cerrone M, Delmar M. Arrhythmogenic cardiomyopathy and Brugada syndrome: diseases of the connexome. FEBS Lett 2014;588:1322-30.

264. Moncayo-Arlandi J, Brugada R. Unmasking the molecular link between arrhythmogenic cardiomyopathy and Brugada syndrome. Nature reviews Cardiology 2017;14:744-756.
265. Gerull B, Kirchner F, Chong JX et al. Homozygous founder mutation in desmocollin-2 (DSC2) causes arrhythmogenic cardiomyopathy in the Hutterite population. Circ Cardiovasc Genet 2013;6:327-36.
266. Beffagna G, Occhi G, Nava A et al. Regulatory mutations in transforming growth factor-beta3 gene cause arrhythmogenic right ventricular cardiomyopathy type 1. Cardiovasc Res 2005;65:366-73.
267. Lazzarini E, Jongbloed JD, Pilichou K et al. The ARVD/C genetic variants database: 2014 update. Hum Mutat 2015;36:403-10.
268. Sheikh F, Ross RS, Chen J. Cell-cell connection to cardiac disease. Trends Cardiovasc Med 2009;19:182-90.
269. Franke WW, Borrmann CM, Grund C, Pieperhoff S. The area composita of adhering junctions connecting heart muscle cells of vertebrates. I. Molecular definition in intercalated disks of cardiomyocytes by immunoelectron microscopy of desmosomal proteins. Eur J Cell Biol 2006;85:69-82.
270. Balse E, Steele DF, Abriel H, Coulombe A, Fedida D, Hatem SN. Dynamic of ion channel expression at the plasma membrane of cardiomyocytes. Physiol Rev 2012;92:1317-58.
271. Knudsen KA, Wheelock MJ. Plakoglobin, or an 83-kD homologue distinct from beta-catenin, interacts with E-cadherin and N-cadherin. J Cell Biol 1992;118:671-9.
272. Borrmann CM, Grund C, Kuhn C, Hofmann I, Pieperhoff S, Franke WW. The area composita of adhering junctions connecting heart muscle cells of vertebrates. II. Colocalizations of desmosomal and fascia adhaerens molecules in the intercalated disk. Eur J Cell Biol 2006;85:469-85.
273. Sacco PA, McGranahan TM, Wheelock MJ, Johnson KR. Identification of plakoglobin domains required for association with N-cadherin and alpha-catenin. J Biol Chem 1995;270:20201-6.
274. Kostetskii I, Li J, Xiong Y et al. Induced deletion of the N-cadherin gene in the heart leads to dissolution of the intercalated disc structure. Circ Res 2005;96:346-54.
275. Li J, Patel VV, Kostetskii I et al. Cardiac-specific loss of N-cadherin leads to alteration in connexins with conduction slowing and arrhythmogenesis. Circ Res 2005;97:474-81.
276. Li J, Levin MD, Xiong Y, Petrenko N, Patel VV, Radice GL. N-cadherin haploinsufficiency affects cardiac gap junctions and arrhythmic susceptibility. J Mol Cell Cardiol 2008;44:597-606.
277. Chen SN, Gurha P, Lombardi R, Ruggiero A, Willerson JT, Marian AJ. The hippo pathway is activated and is a causal mechanism for adipogenesis in arrhythmogenic cardiomyopathy. Circ Res 2014;114:454-68.
278. Tse G. Mechanisms of cardiac arrhythmias. J Arrhythm 2016;32:75-81.
279. Lakatta EG, Vinogradova T, Lyashkov A et al. The integration of spontaneous intracellular Ca2+ cycling and surface membrane ion channel activation entrains normal automaticity in cells of the heart's pacemaker. Ann N Y Acad Sci 2006;1080:178-206.
280. Baruscotti M, Bucchi A, Difrancesco D. Physiology and pharmacology of the cardiac pacemaker ("funny") current. Pharmacol Ther 2005;107:59-79.
281. Vinogradova TM, Maltsev VA, Bogdanov KY, Lyashkov AE, Lakatta EG. Rhythmic Ca2+ oscillations drive sinoatrial nodal cell pacemaker function to make the heart tick. Ann N Y Acad Sci 2005;1047:138-56.
282. Groenke S, Larson ED, Alber S et al. Complete atrial-specific knockout of sodium-calcium exchange eliminates sinoatrial node pacemaker activity. PLoS One 2013;8:e81633.

283. Hamosh A, Scott AF, Amberger J, Bocchini C, Valle D, McKusick VA. Online Mendelian Inheritance in Man (OMIM), a knowledgebase of human genes and genetic disorders. Nucleic acids research 2002;30:52-5.
284. Aronsen JM, Swift F, Sejersted OM. Cardiac sodium transport and excitation-contraction coupling. J Mol Cell Cardiol 2013;61:11-9.
285. Kyle JW, Makielski JC. Diseases caused by mutations in Nav1.5 interacting proteins. Card Electrophysiol Clin 2014;6:797-809.
286. Shi R, Zhang Y, Yang C et al. The cardiac sodium channel mutation delQKP 1507-1509 is associated with the expanding phenotypic spectrum of LQT3, conduction disorder, dilated cardiomyopathy, and high incidence of youth sudden death. Europace : European pacing, arrhythmias, and cardiac electrophysiology : journal of the working groups on cardiac pacing, arrhythmias, and cardiac cellular electrophysiology of the European Society of Cardiology 2008;10:1329-35.
287. Cerrone M, Delmar M. Desmosomes and the sodium channel complex: implications for arrhythmogenic cardiomyopathy and Brugada syndrome. Trends Cardiovasc Med 2014;24:184-90.
288. Maron BJ, Towbin JA, Thiene G et al. Contemporary definitions and classification of the cardiomyopathies: an American Heart Association Scientific Statement from the Council on Clinical Cardiology, Heart Failure and Transplantation Committee; Quality of Care and Outcomes Research and Functional Genomics and Translational Biology Interdisciplinary Working Groups; and Council on Epidemiology and Prevention. Circulation 2006;113:1807-16.
289. Groenewegen WA, Firouzi M, Bezzina CR et al. A cardiac sodium channel mutation cosegregates with a rare connexin40 genotype in familial atrial standstill. Circ Res 2003;92:14-22.
290. Olson TM, Michels VV, Ballew JD et al. Sodium channel mutations and susceptibility to heart failure and atrial fibrillation. JAMA 2005;293:447-54.
291. Shan L, Makita N, Xing Y et al. SCN5A variants in Japanese patients with left ventricular noncompaction and arrhythmia. Mol Genet Metab 2008;93:468-74.
292. Beckermann TM, McLeod K, Murday V, Potet F, George AL, Jr. Novel SCN5A mutation in amiodarone-responsive multifocal ventricular ectopy-associated cardiomyopathy. Heart Rhythm 2014;11:1446-53.
293. Sato PY, Musa H, Coombs W et al. Loss of plakophilin-2 expression leads to decreased sodium current and slower conduction velocity in cultured cardiac myocytes. Circ Res 2009;105:523-6.
294. Cerrone M, Lin X, Zhang M et al. Missense mutations in plakophilin-2 cause sodium current deficit and associate with a Brugada syndrome phenotype. Circulation 2014;129:1092-103.
295. Te Riele AS, Agullo-Pascual E, James CA et al. Multilevel analyses of SCN5A mutations in arrhythmogenic right ventricular dysplasia/cardiomyopathy suggest non-canonical mechanisms for disease pathogenesis. Cardiovasc Res 2017;113:102-111.
296. Leo-Macias A, Agullo-Pascual E, Sanchez-Alonso JL et al. Nanoscale visualization of functional adhesion/excitability nodes at the intercalated disc. Nature communications 2016;7:10342.
297. Spezzacatene A, Sinagra G, Merlo M et al. Arrhythmogenic Phenotype in Dilated Cardiomyopathy: Natural History and Predictors of Life-Threatening Arrhythmias. J Am Heart Assoc 2015;4:e002149.
298. Bang ML, Chen J. Roles of Nebulin Family Members in the Heart. Circ J 2015;79:2081-7.

299. Frank D, Frey N. Cardiac Z-disc signaling network. J Biol Chem 2011;286:9897-904.
300. Frank D, Kuhn C, Katus HA, Frey N. The sarcomeric Z-disc: a nodal point in signalling and disease. J Mol Med (Berl) 2006;84:446-68.
301. Knoll R, Buyandelger B, Lab M. The sarcomeric Z-disc and Z-discopathies. J Biomed Biotechnol 2011;2011:569628.
302. Beggs AH, Byers TJ, Knoll JH, Boyce FM, Bruns GA, Kunkel LM. Cloning and characterization of two human skeletal muscle alpha-actinin genes located on chromosomes 1 and 11. J Biol Chem 1992;267:9281-8.
303. Ribeiro Ede A, Jr., Pinotsis N, Ghisleni A et al. The structure and regulation of human muscle alpha-actinin. Cell 2014;159:1447-60.
304. Knoll R, Buyandelger B. Z-disc transcriptional coupling, sarcomeroptosis and mechanoptosis [corrected]. Cell Biochem Biophys 2013;66:65-71.
305. Luther PK. The vertebrate muscle Z-disc: sarcomere anchor for structure and signalling. J Muscle Res Cell Motil 2009;30:171-85.
306. Sjoblom B, Salmazo A, Djinovic-Carugo K. Alpha-actinin structure and regulation. Cell Mol Life Sci 2008;65:2688-701.
307. Murphy AC, Young PW. The actinin family of actin cross-linking proteins - a genetic perspective. Cell Biosci 2015;5:49.
308. Thompson TG, Chan YM, Hack AA et al. Filamin 2 (FLN2): A muscle-specific sarcoglycan interacting protein. J Cell Biol 2000;148:115-26.
309. Gontier Y, Taivainen A, Fontao L et al. The Z-disc proteins myotilin and FATZ-1 interact with each other and are connected to the sarcolemma via muscle-specific filamins. J Cell Sci 2005;118:3739-49.
310. van der Ven PF, Wiesner S, Salmikangas P et al. Indications for a novel muscular dystrophy pathway. gamma-filamin, the muscle-specific filamin isoform, interacts with myotilin. J Cell Biol 2000;151:235-48.
311. Faulkner G, Pallavicini A, Comelli A et al. FATZ, a filamin-, actinin-, and telethonin-binding protein of the Z-disc of skeletal muscle. J Biol Chem 2000;275:41234-42.
312. Takada F, Vander Woude DL, Tong HQ et al. Myozenin: an alpha-actinin- and gamma-filamin-binding protein of skeletal muscle Z lines. Proc Natl Acad Sci U S A 2001;98:1595-600.
313. Kley RA, Hellenbroich Y, van der Ven PF et al. Clinical and morphological phenotype of the filamin myopathy: a study of 31 German patients. Brain 2007;130:3250-64.
314. Vorgerd M, van der Ven PF, Bruchertseifer V et al. A mutation in the dimerization domain of filamin c causes a novel type of autosomal dominant myofibrillar myopathy. American journal of human genetics 2005;77:297-304.
315. Faulkner G, Pallavicini A, Formentin E et al. ZASP: a new Z-band alternatively spliced PDZ-motif protein. J Cell Biol 1999;146:465-75.
316. Klaavuniemi T, Ylanne J. Zasp/Cypher internal ZM-motif containing fragments are sufficient to co-localize with alpha-actinin--analysis of patient mutations. Exp Cell Res 2006;312:1299-311.
317. Zhou Q, Chu PH, Huang C et al. Ablation of Cypher, a PDZ-LIM domain Z-line protein, causes a severe form of congenital myopathy. J Cell Biol 2001;155:605-12.
318. Zheng M, Cheng H, Li X et al. Cardiac-specific ablation of Cypher leads to a severe form of dilated cardiomyopathy with premature death. Hum Mol Genet 2009;18:701-13.
319. Ziane R, Huang H, Moghadaszadeh B, Beggs AH, Levesque G, Chahine M. Cell membrane expression of cardiac sodium channel Na(v)1.5 is modulated by alpha-actinin-2 interaction. Biochemistry 2010;49:166-78.

320. Arimura T, Hayashi T, Terada H et al. A Cypher/ZASP mutation associated with dilated cardiomyopathy alters the binding affinity to protein kinase C. J Biol Chem 2004;279:6746-52.
321. Xi Y, Ai T, De Lange E et al. Loss of function of hNav1.5 by a ZASP1 mutation associated with intraventricular conduction disturbances in left ventricular noncompaction. Circ Arrhythm Electrophysiol 2012;5:1017-26.
322. Scriven DR, Dan P, Moore ED. Distribution of proteins implicated in excitation-contraction coupling in rat ventricular myocytes. Biophys J 2000;79:2682-91.
323. Brette F, Orchard CH. Density and sub-cellular distribution of cardiac and neuronal sodium channel isoforms in rat ventricular myocytes. Biochem Biophys Res Commun 2006;348:1163-6.
324. Ylanne J, Scheffzek K, Young P, Saraste M. Crystal structure of the alpha-actinin rod reveals an extensive torsional twist. Structure 2001;9:597-604.
325. Perz-Edwards RJ, Reedy MK. Electron microscopy and x-ray diffraction evidence for two Z-band structural states. Biophys J 2011;101:709-17.
326. Cukovic D, Lu GW, Wible B, Steele DF, Fedida D. A discrete amino terminal domain of Kv1.5 and Kv1.4 potassium channels interacts with the spectrin repeats of alpha-actinin-2. FEBS Lett 2001;498:87-92.
327. Maruoka ND, Steele DF, Au BP et al. alpha-actinin-2 couples to cardiac Kv1.5 channels, regulating current density and channel localization in HEK cells. FEBS Lett 2000;473:188-94.
328. Lu L, Zhang Q, Timofeyev V et al. Molecular coupling of a Ca2+-activated K+ channel to L-type Ca2+ channels via alpha-actinin2. Circ Res 2007;100:112-20.
329. Bagnall RD, Molloy LK, Kalman JM, Semsarian C. Exome sequencing identifies a mutation in the ACTN2 gene in a family with idiopathic ventricular fibrillation, left ventricular noncompaction, and sudden death. BMC medical genetics 2014;15:99.
330. Girolami F, Iascone M, Tomberli B et al. Novel alpha-actinin 2 variant associated with familial hypertrophic cardiomyopathy and juvenile atrial arrhythmias: a massively parallel sequencing study. Circ Cardiovasc Genet 2014;7:741-50.
331. Kostin S, Scholz D, Shimada T et al. The internal and external protein scaffold of the T-tubular system in cardiomyocytes. Cell Tissue Res 1998;294:449-60.
332. Solaro RJ, Van Eyk J. Altered interactions among thin filament proteins modulate cardiac function. J Mol Cell Cardiol 1996;28:217-30.
333. Ross RS. The extracellular connections: the role of integrins in myocardial remodeling. Journal of cardiac failure 2002;8:S326-31.
334. Korte FS, McDonald KS, Harris SP, Moss RL. Loaded shortening, power output, and rate of force redevelopment are increased with knockout of cardiac myosin binding protein-C. Circ Res 2003;93:752-8.
335. Capetanaki Y. Desmin cytoskeleton: a potential regulator of muscle mitochondrial behavior and function. Trends Cardiovasc Med 2002;12:339-48.
336. Brodehl A, Dieding M, Klauke B et al. The novel desmin mutant p.A120D impairs filament formation, prevents intercalated disk localization, and causes sudden cardiac death. Circ Cardiovasc Genet 2013;6:615-23.
337. Bermudez-Jimenez FJ, Carriel V, Brodehl A et al. Novel Desmin Mutation p.Glu401Asp Impairs Filament Formation, Disrupts Cell Membrane Integrity, and Causes Severe Arrhythmogenic Left Ventricular Cardiomyopathy/Dysplasia. Circulation 2018;137:1595-1610.

338. Levin J, Bulst S, Thirion C et al. Divergent molecular effects of desmin mutations on protein assembly in myofibrillar myopathy. J Neuropathol Exp Neurol 2010;69:415-24.
339. McNally EM, Mestroni L. Dilated Cardiomyopathy: Genetic Determinants and Mechanisms. Circ Res 2017;121:731-748.
340. Klauke B, Kossmann S, Gaertner A et al. De novo desmin-mutation N116S is associated with arrhythmogenic right ventricular cardiomyopathy. Hum Mol Genet 2010;19:4595-607.
341. Brodehl A, Hedde PN, Dieding M et al. Dual color photoactivation localization microscopy of cardiomyopathy-associated desmin mutants. J Biol Chem 2012;287:16047-57.
342. van Spaendonck-Zwarts KY, van der Kooi AJ, van den Berg MP et al. Recurrent and founder mutations in the Netherlands: the cardiac phenotype of DES founder mutations p.S13F and p.N342D. Neth Heart J 2012;20:219-28.
343. Dalakas MC, Park KY, Semino-Mora C, Lee HS, Sivakumar K, Goldfarb LG. Desmin myopathy, a skeletal myopathy with cardiomyopathy caused by mutations in the desmin gene. N Engl J Med 2000;342:770-80.
344. Otten E, Asimaki A, Maass A et al. Desmin mutations as a cause of right ventricular heart failure affect the intercalated disks. Heart Rhythm 2010;7:1058–64.
345. Seidman CE, Seidman JG. Identifying sarcomere gene mutations in hypertrophic cardiomyopathy: a personal history. Circ Res 2011;108:743-50.
346. Alfares AA, Kelly MA, McDermott G et al. Results of clinical genetic testing of 2,912 probands with hypertrophic cardiomyopathy: expanded panels offer limited additional sensitivity. Genet Med 2015;17:880-8.
347. Ingles J, Burns C, Bagnall RD et al. Nonfamilial Hypertrophic Cardiomyopathy: Prevalence, Natural History, and Clinical Implications. Circ Cardiovasc Genet 2017;10.
348. Lek M, Karczewski KJ, Minikel EV et al. Analysis of protein-coding genetic variation in 60,706 humans. Nature 2016;536:285-91.
349. Miller EM, Hinton RB, Czosek R et al. Genetic Testing in Pediatric Left Ventricular Noncompaction. Circ Cardiovasc Genet 2017;10.
350. Probst S, Oechslin E, Schuler P et al. Sarcomere gene mutations in isolated left ventricular noncompaction cardiomyopathy do not predict clinical phenotype. Circ Cardiovasc Genet 2011;4:367-74.
351. Kaski JP, Syrris P, Burch M et al. Idiopathic restrictive cardiomyopathy in children is caused by mutations in cardiac sarcomere protein genes. Heart 2008;94:1478-84.
352. Ko C, Arscott P, Concannon M et al. Genetic testing impacts the utility of prospective familial screening in hypertrophic cardiomyopathy through identification of a nonfamilial subgroup. Genet Med 2018;20:69-75.
353. van Waning JI, Caliskan K, Hoedemaekers YM et al. Genetics, Clinical Features, and Long-Term Outcome of Noncompaction Cardiomyopathy. J Am Coll Cardiol 2018;71:711-722.
354. Wang C, Hata Y, Hirono K et al. A Wide and Specific Spectrum of Genetic Variants and Genotype-Phenotype Correlations Revealed by Next-Generation Sequencing in Patients with Left Ventricular Noncompaction. J Am Heart Assoc 2017;6.
355. Bonnet D, Martin D, Pascale De L et al. Arrhythmias and conduction defects as presenting symptoms of fatty acid oxidation disorders in children. Circulation 1999;100:2248-53.
356. DaTorre SD, Creer MH, Pogwizd SM, Corr PB. Amphipathic lipid metabolites and their relation to arrhythmogenesis in the ischemic heart. J Mol Cell Cardiol 1991;23 Suppl 1:11-22.

357. Arita M, Sato T, Ishida H, Nakazawa H. [Cellular electrophysiological basis of proarrhythmic and antiarrhythmic effects of ischemia-related lipid metabolites]. Rinsho Byori 1993;41:401-8.
358. Huang JM, Xian H, Bacaner M. Long-chain fatty acids activate calcium channels in ventricular myocytes. Proc Natl Acad Sci U S A 1992;89:6452-6.
359. Schmilinsky-Fluri G, Valiunas V, Willi M, Weingart R. Modulation of cardiac gap junctions: the mode of action of arachidonic acid. J Mol Cell Cardiol 1997;29:1703-13.
360. Frigeni M, Balakrishnan B, Yin X et al. Functional and molecular studies in primary carnitine deficiency. Hum Mutat 2017;38:1684-1699.
361. Longo N, Frigeni M, Pasquali M. Carnitine transport and fatty acid oxidation. Biochim Biophys Acta 2016;1863:2422-35.
362. Holmgren D, Wahlander H, Eriksson BO, Oldfors A, Holme E, Tulinius M. Cardiomyopathy in children with mitochondrial disease; clinical course and cardiological findings. European heart journal 2003;24:280-8.
363. Debray FG, Lambert M, Chevalier I et al. Long-term outcome and clinical spectrum of 73 pediatric patients with mitochondrial diseases. Pediatrics 2007;119:722-33.
364. El-Hattab AW, Scaglia F. Mitochondrial cytopathies. Cell Calcium 2016;60:199-206.
365. Munnich A, Rotig A, Chretien D et al. Clinical presentation of mitochondrial disorders in childhood. J Inherit Metab Dis 1996;19:521-7.
366. Jackson MJ, Schaefer JA, Johnson MA, Morris AA, Turnbull DM, Bindoff LA. Presentation and clinical investigation of mitochondrial respiratory chain disease. A study of 51 patients. Brain 1995;118 (Pt 2):339-57.
367. DiMauro S, Bonilla E, De Vivo DC. Does the patient have a mitochondrial encephalomyopathy? J Child Neurol 1999;14 Suppl 1:S23-35.
368. Koenig MK. Presentation and diagnosis of mitochondrial disorders in children. Pediatr Neurol 2008;38:305-13.
369. Petty RK, Harding AE, Morgan-Hughes JA. The clinical features of mitochondrial myopathy. Brain 1986;109 (Pt 5):915-38.
370. Hsu CH, Kwon H, Perng CL, Bai RK, Dai P, Wong LJ. Hearing loss in mitochondrial disorders. Ann N Y Acad Sci 2005;1042:36-47.
371. Wahbi K, Larue S, Jardel C et al. Cardiac involvement is frequent in patients with the m.8344A>G mutation of mitochondrial DNA. Neurology 2010;74:674-7.
372. Anan R, Nakagawa M, Miyata M et al. Cardiac involvement in mitochondrial diseases. A study on 17 patients with documented mitochondrial DNA defects. Circulation 1995;91:955-61.
373. Stollberger C, Finsterer J, Blazek G. Left ventricular hypertrabeculation/noncompaction and association with additional cardiac abnormalities and neuromuscular disorders. Am J Cardiol 2002;90:899-902.
374. Thavendiranathan P, Dahiya A, Phelan D, Desai MY, Tang WH. Isolated left ventricular non-compaction controversies in diagnostic criteria, adverse outcomes and management. Heart 2013;99:681-9.
375. Kohli SK, Pantazis AA, Shah JS et al. Diagnosis of left-ventricular non-compaction in patients with left-ventricular systolic dysfunction: time for a reappraisal of diagnostic criteria? European heart journal 2008;29:89-95.
376. Arbustini E, Diegoli M, Fasani R et al. Mitochondrial DNA mutations and mitochondrial abnormalities in dilated cardiomyopathy. Am J Pathol 1998;153:1501-10.
377. Huss JM, Kelly DP. Mitochondrial energy metabolism in heart failure: a question of balance. The Journal of clinical investigation 2005;115:547-55.

378. Rustin P, Chretien D, Bourgeron T et al. Assessment of the mitochondrial respiratory chain. Lancet 1991;338:60.
379. Chinnery P, Majamaa K, Turnbull D, Thorburn D. Treatment for mitochondrial disorders. Cochrane Database Syst Rev 2006:CD004426.
380. Martin DS, Grocott MP. Oxygen therapy in critical illness: precise control of arterial oxygenation and permissive hypoxemia. Crit Care Med 2013;41:423-32.
381. Koga Y, Povalko N, Nishioka J, Katayama K, Kakimoto N, Matsuishi T. MELAS and L-arginine therapy: pathophysiology of stroke-like episodes. Ann N Y Acad Sci 2010;1201:104-10.
382. Golden AS, Law YM, Shurtleff H, Warner M, Saneto RP. Mitochondrial electron transport chain deficiency, cardiomyopathy, and long-term cardiac transplant outcome. Pediatr Transplant 2012;16:265-8.
383. Khambatta S, Nguyen DL, Beckman TJ, Wittich CM. Kearns-Sayre syndrome: a case series of 35 adults and children. Int J Gen Med 2014;7:325-32.
384. Kabunga P, Lau AK, Phan K et al. Systematic review of cardiac electrical disease in Kearns-Sayre syndrome and mitochondrial cytopathy. Int J Cardiol 2015;181:303-10.
385. Davis RL, Sue CM. The genetics of mitochondrial disease. Semin Neurol 2011;31:519-30.
386. Bove KE, Schwartz DC. Focal lipid cardiomyopathy in an infant with paroxysmal atrial tachycardia. Arch Pathol 1973;95:26-36.
387. Ferrans VJ, McAllister HA, Jr., Haese WH. Infantile cardiomyopathy with histiocytoid change in cardiac muscle cells. Report of six patients. Circulation 1976;53:708-19.
388. Shehata BM, Patterson K, Thomas JE, Scala-Barnett D, Dasu S, Robinson HB. Histiocytoid cardiomyopathy: three new cases and a review of the literature. Pediatr Dev Pathol 1998;1:56-69.
389. Shehata BM, Bouzyk M, Shulman SC et al. Identification of candidate genes for histiocytoid cardiomyopathy (HC) using whole genome expression analysis: analyzing material from the HC registry. Pediatr Dev Pathol 2011;14:370-7.
390. Gelb AB, Van Meter SH, Billingham ME, Berry GJ, Rouse RV. Infantile histiocytoid cardiomyopathy--myocardial or conduction system hamartoma: what is the cell type involved? Hum Pathol 1993;24:1226-31.
391. Zimmermann A, Diem P, Cottier H. Congenital "histiocytoid" cardiomyopathy: evidence suggesting a developmental disorder of the Purkinje cell system of the heart. Virchows Arch A Pathol Anat Histol 1982;396:187-95.
392. Malhotra V, Ferrans VJ, Virmani R. Infantile histiocytoid cardiomyopathy: three cases and literature review. Am Heart J 1994;128:1009-21.
393. MacMahon HE. Infantile xanthomatous cardiomyopathy. Pediatrics 1971;48:312-5.
394. Andreu AL, Checcarelli N, Iwata S, Shanske S, DiMauro S. A missense mutation in the mitochondrial cytochrome b gene in a revisited case with histiocytoid cardiomyopathy. Pediatr Res 2000;48:311-4.
395. Vallance P. Nitric oxide synthesised from L-arginine mediates endothelium dependent dilatation in human veins in vivo. Cardiovasc Res 2000;45:143-7.
396. Ruszkiewicz AR, Vernon-Roberts E. Sudden death in an infant due to histiocytoid cardiomyopathy. A light-microscopic, ultrastructural, and immunohistochemical study. Am J Forensic Med Pathol 1995;16:74-80.
397. Prahlow JA, Teot LA. Histiocytoid cardiomyopathy: case report and literature review. J Forensic Sci 1993;38:1427-35.
398. Heifetz SA, Faught PR, Bauman M. Pathological case of the month. Histiocytoid (oncocytic) cardiomyopathy. Arch Pediatr Adolesc Med 1995;149:464-5.

399. Suarez V, Fuggle WJ, Cameron AH, French TA, Hollingworth T. Foamy myocardial transformation of infancy: an inherited disease. J Clin Pathol 1987;40:329-34.
400. Franciosi RA, Singh A. Oncocytic cardiomyopathy syndrome. Hum Pathol 1988;19:1361-2.
401. Grech V, Chan MK, Vella C, Attard Montalto S, Rees P, Trompeter RS. Cardiac malformations associated with the congenital nephrotic syndrome. Pediatr Nephrol 2000;14:1115-7.
402. Ferrans VJ. Pathologic anatomy of the dilated cardiomyopathies. Am J Cardiol 1989;64:9C-11C.
403. Saffitz JE, Ferrans VJ, Rodriguez ER, Lewis FR, Roberts WC. Histiocytoid cardiomyopathy: a cause of sudden death in apparently healthy infants. Am J Cardiol 1983;52:215-7.
404. Kauffman SL, Chandra N, Peress NS, Rodriguez-Torres R. Idiopathic infantile cardiomyopathy with involvement of the conduction system. Am J Cardiol 1972;30:648-52.
405. Van Hare GF. Radiofrequency catheter ablation of cardiac arrhythmias in pediatric patients. Adv Pediatr 1994;41:83-109.
406. Shehata BM, Cundiff CA, Lee K et al. Exome sequencing of patients with histiocytoid cardiomyopathy reveals a de novo NDUFB11 mutation that plays a role in the pathogenesis of histiocytoid cardiomyopathy. Am J Med Genet A 2015;167A:2114-21.
407. Falk RH, Alexander KM, Liao R, Dorbala S. AL (Light-Chain) Cardiac Amyloidosis: A Review of Diagnosis and Therapy. J Am Coll Cardiol 2016;68:1323-41.
408. Gertz MA, Benson MD, Dyck PJ et al. Diagnosis, Prognosis, and Therapy of Transthyretin Amyloidosis. J Am Coll Cardiol 2015;66:2451-2466.
409. Rocken C, Peters B, Juenemann G et al. Atrial amyloidosis: an arrhythmogenic substrate for persistent atrial fibrillation. Circulation 2002;106:2091-7.
410. Park J, Lee SH, Lee JS et al. High recurrence of atrial fibrillation in patients with high tissue atrial natriuretic peptide and amyloid levels after concomitant maze and mitral valve surgery. J Cardiol 2017;69:345-352.
411. Grogan M, Dispenzieri A. Natural history and therapy of AL cardiac amyloidosis. Heart Fail Rev 2015;20:155-62.
412. Adams D, Gonzalez-Duarte A, O'Riordan WD et al. Patisiran, an RNAi Therapeutic, for Hereditary Transthyretin Amyloidosis. N Engl J Med 2018;379:11-21.
413. Benson MD, Waddington-Cruz M, Berk JL et al. Inotersen Treatment for Patients with Hereditary Transthyretin Amyloidosis. N Engl J Med 2018;379:22-31.
414. Buxbaum JN. Oligonucleotide Drugs for Transthyretin Amyloidosis. N Engl J Med 2018;379:82-85.
415. Maurer MS, Sultan MB, Rapezzi C. Tafamidis for Transthyretin Amyloid Cardiomyopathy. N Engl J Med 2019;380:196-197.
416. Maurer MS, Schwartz JH, Gundapaneni B et al. Tafamidis Treatment for Patients with Transthyretin Amyloid Cardiomyopathy. N Engl J Med 2018;379:1007-1016.
417. Mueller PS, Edwards WD, Gertz MA. Symptomatic ischemic heart disease resulting from obstructive intramural coronary amyloidosis. Am J Med 2000;109:181-8.
418. Reisinger J, Dubrey SW, Lavalley M, Skinner M, Falk RH. Electrophysiologic abnormalities in AL (primary) amyloidosis with cardiac involvement. J Am Coll Cardiol 1997;30:1046-51.
419. Mathew V, Chaliki H, Nishimura RA. Atrioventricular sequential pacing in cardiac amyloidosis: an acute Doppler echocardiographic and catheterization hemodynamic study. Clin Cardiol 1997;20:723-5.

420. Mathew V, Olson LJ, Gertz MA, Hayes DL. Symptomatic conduction system disease in cardiac amyloidosis. Am J Cardiol 1997;80:1491-2.
421. Rezk T, Whelan CJ, Lachmann HJ et al. Role of implantable intracardiac defibrillators in patients with cardiac immunoglobulin light chain amyloidosis. Br J Haematol 2017.
422. Mohammed SF, Mirzoyev SA, Edwards WD et al. Left ventricular amyloid deposition in patients with heart failure and preserved ejection fraction. JACC Heart Fail 2014;2:113-22.
423. Li JP, Galvis ML, Gong F et al. In vivo fragmentation of heparan sulfate by heparanase overexpression renders mice resistant to amyloid protein A amyloidosis. Proc Natl Acad Sci U S A 2005;102:6473-7.
424. Penchala SC, Connelly S, Wang Y et al. AG10 inhibits amyloidogenesis and cellular toxicity of the familial amyloid cardiomyopathy-associated V122I transthyretin. Proc Natl Acad Sci U S A 2013;110:9992-7.
425. Ton VK, Mukherjee M, Judge DP. Transthyretin cardiac amyloidosis: pathogenesis, treatments, and emerging role in heart failure with preserved ejection fraction. Clin Med Insights Cardiol 2014;8:39-44.
426. Eriksson A, Eriksson P, Olofsson BO, Thornell LE. The sinoatrial node in familial amyloidosis with polyneuropathy. A clinico-pathological study of nine cases from northern Sweden. Virchows Arch A Pathol Anat Histopathol 1984;402:239-46.
427. Eriksson P, Olofsson BO. Pacemaker treatment in familial amyloidosis with polyneuropathy. Pacing Clin Electrophysiol 1984;7:702-6.
428. Olofsson BO, Eriksson P, Eriksson A. The sick sinus syndrome in familial amyloidosis with polyneuropathy. Int J Cardiol 1983;4:71-3.
429. Barbhaiya CR, Kumar S, Baldinger SH et al. Electrophysiologic assessment of conduction abnormalities and atrial arrhythmias associated with amyloid cardiomyopathy. Heart Rhythm 2016;13:383-90.
430. Capone R, Amsterdam EA, Mason DT, Zelis R. Systemic amyloidosis, functional coronary insufficiency, and autonomic impairment. Annals of internal medicine 1972;76:599-603.
431. French JM, Hall G, Parish DJ, Smith WT. PERIPHERAL AND AUTONOMIC NERVE INVOLVEMENT IN PRIMARY AMYLOIDOSIS ASSOCIATED WITH UNCONTROLLABLE DIARRHOEA AND STEATORRHOEA. Am J Med 1965;39:277-84.
432. Wang AK, Fealey RD, Gehrking TL, Low PA. Patterns of neuropathy and autonomic failure in patients with amyloidosis. Mayo Clin Proc 2008;83:1226-30.
433. Gertz MA, Falk RH, Skinner M, Cohen AS, Kyle RA. Worsening of congestive heart failure in amyloid heart disease treated by calcium channel-blocking agents. Am J Cardiol 1985;55:1645.
434. Pollak A, Falk RH. Left ventricular systolic dysfunction precipitated by verapamil in cardiac amyloidosis. Chest 1993;104:618-20.
435. Griffiths BE, Hughes P, Dowdle R, Stephens MR. Cardiac amyloidosis with asymmetrical septal hypertrophy and deterioration after nifedipine. Thorax 1982;37:711-2.
436. Tan NY, Mohsin Y, Hodge DO et al. Catheter Ablation for Atrial Arrhythmias in Patients With Cardiac Amyloidosis. Journal of cardiovascular electrophysiology 2016;27:1167-1173.
437. Dubrey SW, Cha K, Anderson J et al. The clinical features of immunoglobulin light-chain (AL) amyloidosis with heart involvement. QJM 1998;91:141-57.
438. Hamon D, Algalarrondo V, Gandjbakhch E et al. Outcome and incidence of appropriate implantable cardioverter-defibrillator therapy in patients with cardiac amyloidosis. Int J Cardiol 2016;222:562-568.

439. Kristen AV, Dengler TJ, Hegenbart U et al. Prophylactic implantation of cardioverter-defibrillator in patients with severe cardiac amyloidosis and high risk for sudden cardiac death. Heart Rhythm 2008;5:235-40.
440. Lin G, Dispenzieri A, Brady PA. Successful termination of a ventricular arrhythmia by implantable cardioverter defibrillator therapy in a patient with cardiac amyloidosis: insight into mechanisms of sudden death. European heart journal 2010;31:1538.
441. Patel KS, Hawkins PN, Whelan CJ, Gillmore JD. Life-saving implantable cardioverter defibrillator therapy in cardiac AL amyloidosis. BMJ Case Rep 2014;2014.
442. Varr BC, Zarafshar S, Coakley T et al. Implantable cardioverter-defibrillator placement in patients with cardiac amyloidosis. Heart Rhythm 2014;11:158-62.
443. Feng D, Edwards WD, Oh JK et al. Intracardiac thrombosis and embolism in patients with cardiac amyloidosis. Circulation 2007;116:2420-6.
444. Zubkov AY, Rabinstein AA, Dispenzieri A, Wijdicks EF. Primary systemic amyloidosis with ischemic stroke as a presenting complication. Neurology 2007;69:1136-41.
445. Sayed RH, Rogers D, Khan F et al. A study of implanted cardiac rhythm recorders in advanced cardiac AL amyloidosis. European heart journal 2015;36:1098-105.
446. Muchtar E, Gertz MA, Kumar SK et al. Digoxin use in systemic light-chain (AL) amyloidosis: contra-indicated or cautious use? Amyloid : the international journal of experimental and clinical investigation : the official journal of the International Society of Amyloidosis 2018:1-7.
447. Tukkie R, Sogaard P, Vleugels J, de Groot IK, Wilde AA, Tan HL. Delay in right ventricular activation contributes to Brugada syndrome. Circulation 2004;109:1272-7.
448. Papavassiliu T, Veltmann C, Doesch C et al. Spontaneous type 1 electrocardiographic pattern is associated with cardiovascular magnetic resonance imaging changes in Brugada syndrome. Heart Rhythm 2010;7:1790-6.
449. Catalano O, Antonaci S, Moro G et al. Magnetic resonance investigations in Brugada syndrome reveal unexpectedly high rate of structural abnormalities. European heart journal 2009;30:2241-8.
450. van Hoorn F, Campian ME, Spijkerboer A et al. SCN5A mutations in Brugada syndrome are associated with increased cardiac dimensions and reduced contractility. PLoS One 2012;7:e42037.
451. Nademanee K, Veerakul G, Chandanamattha P et al. Prevention of ventricular fibrillation episodes in Brugada syndrome by catheter ablation over the anterior right ventricular outflow tract epicardium. Circulation 2011;123:1270-9.
452. Nademanee K, Raju H, de Noronha SV et al. Fibrosis, Connexin-43, and Conduction Abnormalities in the Brugada Syndrome. J Am Coll Cardiol 2015;66:1976-1986.
453. Ohkubo K, Watanabe I, Okumura Y et al. Right ventricular histological substrate and conduction delay in patients with Brugada syndrome. Int Heart J 2010;51:17-23.
454. Zumhagen S, Spieker T, Rolinck J et al. Absence of pathognomonic or inflammatory patterns in cardiac biopsies from patients with Brugada syndrome. Circ Arrhythm Electrophysiol 2009;2:16–23.
455. Frustaci A, Priori SG, Pieroni M et al. Cardiac histological substrate in patients with clinical phenotype of Brugada syndrome. Circulation 2005;112:3680-7.
456. Corrado D, Zorzi A, Cerrone M et al. Relationship Between Arrhythmogenic Right Ventricular Cardiomyopathy and Brugada Syndrome: New Insights From Molecular Biology and Clinical Implications. Circ Arrhythm Electrophysiol 2016;9:e003631.
457. Xiong Q, Cao Q, Zhou Q et al. Arrhythmogenic cardiomyopathy in a patient with a rare loss-of-function KCNQ1 mutation. J Am Heart Assoc 2015;4:e001526.

458. Schmitt N, Schwarz M, Peretz A, Abitbol I, Attali B, Pongs O. A recessive C-terminal Jervell and Lange-Nielsen mutation of the KCNQ1 channel impairs subunit assembly. EMBO J 2000;19:332-40.
459. Chen YH, Xu SJ, Bendahhou S et al. KCNQ1 gain-of-function mutation in familial atrial fibrillation. Science 2003;299:251-4.
460. Barhanin J, Lesage F, Guillemare E, Fink M, Lazdunski M, Romey G. K(V)LQT1 and IsK (minK) proteins associate to form the I(Ks) cardiac potassium current. Nature 1996;384:78-80.
461. Bellocq C, van Ginneken AC, Bezzina CR et al. Mutation in the KCNQ1 gene leading to the short QT-interval syndrome. Circulation 2004;109:2394-7.
462. Bartos DC, Anderson JB, Bastiaenen R et al. A KCNQ1 mutation causes a high penetrance for familial atrial fibrillation. Journal of cardiovascular electrophysiology 2013;24:562-9.
463. Das S, Makino S, Melman YF et al. Mutation in the S3 segment of KCNQ1 results in familial lone atrial fibrillation. Heart Rhythm 2009;6:1146-53.
464. Bagnall RD, Das KJ, Duflou J, Semsarian C. Exome analysis-based molecular autopsy in cases of sudden unexplained death in the young. Heart Rhythm 2014;11:655-62.
465. Kharbanda M, Hunter A, Tennant S et al. Long QT syndrome and left ventricular noncompaction in 4 family members across 2 generations with KCNQ1 mutation. Eur J Med Genet 2017;60:233-238.
466. Nakashima K, Kusakawa I, Yamamoto T et al. A left ventricular noncompaction in a patient with long QT syndrome caused by a KCNQ1 mutation: a case report. Heart Vessels 2013;28:126-9.
467. Ogawa K, Nakamura Y, Terano K, Ando T, Hishitani T, Hoshino K. Isolated non-compaction of the ventricular myocardium associated with long QT syndrome: a report of 2 cases. Circ J 2009;73:2169-72.
468. Clapham DE, Julius D, Montell C, Schultz G. International Union of Pharmacology. XLIX. Nomenclature and structure-function relationships of transient receptor potential channels. Pharmacol Rev 2005;57:427-50.
469. Ramsey IS, Delling M, Clapham DE. An introduction to TRP channels. Annu Rev Physiol 2006;68:619-47.
470. Abriel H, Syam N, Sottas V, Amarouch MY, Rougier JS. TRPM4 channels in the cardiovascular system: physiology, pathophysiology, and pharmacology. Biochem Pharmacol 2012;84:873-81.
471. Murakami M, Xu F, Miyoshi I, Sato E, Ono K, Iijima T. Identification and characterization of the murine TRPM4 channel. Biochem Biophys Res Commun 2003;307:522-8.
472. Nilius B, Prenen J, Voets T, Droogmans G. Intracellular nucleotides and polyamines inhibit the Ca2+-activated cation channel TRPM4b. Pflugers Arch 2004;448:70-5.
473. Kruse M, Schulze-Bahr E, Corfield V et al. Impaired endocytosis of the ion channel TRPM4 is associated with human progressive familial heart block type I. The Journal of clinical investigation 2009;119:2737-44.
474. Liu H, El Zein L, Kruse M et al. Gain-of-function mutations in TRPM4 cause autosomal dominant isolated cardiac conduction disease. Circ Cardiovasc Genet 2010;3:374-85.
475. Stallmeyer B, Zumhagen S, Denjoy I et al. Mutational spectrum in the Ca(2+)--activated cation channel gene TRPM4 in patients with cardiac conductance disturbances. Hum Mutat 2012;33:109-17.
476. Liu H, Chatel S, Simard C et al. Molecular genetics and functional anomalies in a series of 248 Brugada cases with 11 mutations in the TRPM4 channel. PLoS One 2013;8:e54131.

477. Daumy X, Amarouch MY, Lindenbaum P et al. Targeted resequencing identifies TRPM4 as a major gene predisposing to progressive familial heart block type I. Int J Cardiol 2016;207:349-58.
478. Forleo C, D'Erchia AM, Sorrentino S et al. Targeted next-generation sequencing detects novel gene-phenotype associations and expands the mutational spectrum in cardiomyopathies. PLoS One 2017;12:e0181842.
479. Saito Y, Nakamura K, Nishi N et al. TRPM4 Mutation in Patients With Ventricular Noncompaction and Cardiac Conduction Disease. Circ Genom Precis Med 2018;11:e002103.
480. MacLennan DH, Kranias EG. Phospholamban: a crucial regulator of cardiac contractility. Nat Rev Mol Cell Biol 2003;4:566-77.
481. Haghighi K, Kolokathis F, Gramolini AO et al. A mutation in the human phospholamban gene, deleting arginine 14, results in lethal, hereditary cardiomyopathy. Proc Natl Acad Sci U S A 2006;103:1388-93.
482. Posch MG, Perrot A, Geier C et al. Genetic deletion of arginine 14 in phospholamban causes dilated cardiomyopathy with attenuated electrocardiographic R amplitudes. Heart Rhythm 2009;6:480-6.
483. Groeneweg JA, van der Zwaag PA, Jongbloed JD et al. Left-dominant arrhythmogenic cardiomyopathy in a large family: associated desmosomal or nondesmosomal genotype? Heart Rhythm 2013;10:548-59.
484. Medeiros A, Biagi DG, Sobreira TJ et al. Mutations in the human phospholamban gene in patients with heart failure. Am Heart J 2011;162:1088-1095 e1.
485. Sepehrkhouy S, Gho J, van Es R et al. Distinct fibrosis pattern in desmosomal and phospholamban mutation carriers in hereditary cardiomyopathies. Heart Rhythm 2017;14:1024-1032.
486. Basso C, Thiene G, Corrado D, Angelini A, Nava A, Valente M. Arrhythmogenic right ventricular cardiomyopathy. Dysplasia, dystrophy, or myocarditis? Circulation 1996;94:983-91.
487. Pilichou K, Bezzina CR, Thiene G, Basso C. Arrhythmogenic cardiomyopathy: transgenic animal models provide novel insights into disease pathobiology. Circ Cardiovasc Genet 2011;4:318-26.
488. Mast TP, Teske AJ, vd Heijden JF et al. Left Ventricular Involvement in Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy Assessed by Echocardiography Predicts Adverse Clinical Outcome. J Am Soc Echocardiogr 2015;28:1103-13 e9.
489. Te Riele AS, James CA, Philips B et al. Mutation-positive arrhythmogenic right ventricular dysplasia/cardiomyopathy: the triangle of dysplasia displaced. Journal of cardiovascular electrophysiology 2013;24:1311–20.
490. Sen-Chowdhry S, Syrris P, Prasad SK et al. Left-dominant arrhythmogenic cardiomyopathy: an under-recognized clinical entity. J Am Coll Cardiol 2008;52:2175-87.
491. Gho JM, van Es R, Stathonikos N et al. High resolution systematic digital histological quantification of cardiac fibrosis and adipose tissue in phospholamban p.Arg14del mutation associated cardiomyopathy. PLoS One 2014;9:e94820.
492. Te Rijdt WP, van Tintelen JP, Vink A et al. Phospholamban p.Arg14del cardiomyopathy is characterized by phospholamban aggregates, aggresomes, and autophagic degradation. Histopathology 2016;69:542-50.
493. Groeneweg JA, van der Zwaag PA, Olde Nordkamp LR et al. Arrhythmogenic right ventricular dysplasia/cardiomyopathy according to revised 2010 task force criteria with

inclusion of non-desmosomal phospholamban mutation carriers. Am J Cardiol 2013;112:1197-206.
494. La Gerche A, Heidbuchel H, Burns AT et al. Disproportionate exercise load and remodeling of the athlete's right ventricle. Medicine and science in sports and exercise 2011;43:974-81.
495. Bartram U, Bauer J, Schranz D. Primary noncompaction of the ventricular myocardium from the morphogenetic standpoint. Pediatric cardiology 2007;28:325-32.
496. Maron BJ, Towbin JA, Thiene G et al. Contemporary definitions and classification of the cardiomyopathies: an American Heart Association Scientific Statement from the Council on Clinical Cardiology, Heart Failure and Transplantation Committee; Quality of Care and Outcomes Research and Functional Genomics and Translational Biology Interdisciplinary Working Groups; and Council on Epidemiology and Prevention. Circulation 2006;113:1807-16.
497. McLaughlin HM, Funke BH. Chapter 17 - Molecular Testing in Inherited Cardiomyopathies. In: Coleman WB, Tsongalis GJ, editors. Diagnostic Molecular Pathology: Academic Press, 2017:213-220.
498. Petersen SE, Selvanayagam JB, Wiesmann F et al. Left ventricular non-compaction: insights from cardiovascular magnetic resonance imaging. J Am Coll Cardiol 2005;46:101-5.
499. Finsterer J, Stollberger C, Towbin JA. Left ventricular noncompaction cardiomyopathy: cardiac, neuromuscular, and genetic factors. Nature reviews Cardiology 2017;14:224-237.
500. Towbin JA, Lorts A, Jefferies JL. Left ventricular non-compaction cardiomyopathy. Lancet 2015;386:813-25.
501. Towbin JA, Jefferies JL. Cardiomyopathies Due to Left Ventricular Noncompaction, Mitochondrial and Storage Diseases, and Inborn Errors of Metabolism. Circ Res 2017;121:838-854.
502. Towbin JA. Left ventricular noncompaction: a new form of heart failure. Heart failure clinics 2010;6:453-69, viii.
503. Kawel N, Nacif M, Arai AE et al. Trabeculated (noncompacted) and compact myocardium in adults: the multi-ethnic study of atherosclerosis. Circulation Cardiovascular imaging 2012;5:357-66.
504. Weir-McCall JR, Yeap PM, Papagiorcopulo C et al. Left Ventricular Noncompaction: Anatomical Phenotype or Distinct Cardiomyopathy? J Am Coll Cardiol 2016;68:2157-2165.
505. Pignatelli RH, McMahon CJ, Dreyer WJ et al. Clinical characterization of left ventricular noncompaction in children: a relatively common form of cardiomyopathy. Circulation 2003;108:2672-8.
506. Hoedemaekers YM, Caliskan K, Michels M et al. The importance of genetic counseling, DNA diagnostics, and cardiologic family screening in left ventricular noncompaction cardiomyopathy. Circ Cardiovasc Genet 2010;3:232-9.
507. Rhee JW, Grove ME, Ashley EA. Navigating Genetic and Phenotypic Uncertainty in Left Ventricular Noncompaction. Circ Cardiovasc Genet 2017;10.
508. Miszalski-Jamka K, Jefferies JL, Mazur W et al. Novel Genetic Triggers and Genotype-Phenotype Correlations in Patients With Left Ventricular Noncompaction. Circ Cardiovasc Genet 2017;10.
509. Bainbridge MN, Davis EE, Choi WY et al. Loss of Function Mutations in NNT Are Associated With Left Ventricular Noncompaction. Circ Cardiovasc Genet 2015;8:544-52.

510. Caliskan K, Szili-Torok T, Theuns DA et al. Indications and outcome of implantable cardioverter-defibrillators for primary and secondary prophylaxis in patients with noncompaction cardiomyopathy. Journal of cardiovascular electrophysiology 2011;22:898-904.
511. Brescia ST, Rossano JW, Pignatelli R et al. Mortality and sudden death in pediatric left ventricular noncompaction in a tertiary referral center. Circulation 2013;127:2202-8.
512. Andreini D, Pontone G, Bogaert J et al. Long-Term Prognostic Value of Cardiac Magnetic Resonance in Left Ventricle Noncompaction: A Prospective Multicenter Study. J Am Coll Cardiol 2016;68:2166-2181.
513. Steffel J, Duru F. Rhythm disorders in isolated left ventricular noncompaction. Ann Med 2012;44:101-8.
514. Bhatia NL, Tajik AJ, Wilansky S, Steidley DE, Mookadam F. Isolated noncompaction of the left ventricular myocardium in adults: a systematic overview. Journal of cardiac failure 2011;17:771-8.
515. Muser D, Liang JJ, Witschey WR et al. Ventricular arrhythmias associated with left ventricular noncompaction: Electrophysiologic characteristics, mapping, and ablation. Heart Rhythm 2017;14:166-175.
516. Gleva MJ, Wang Y, Curtis JP, Berul CI, Huddleston CB, Poole JE. Complications Associated With Implantable Cardioverter Defibrillators in Adults With Congenital Heart Disease or Left Ventricular Noncompaction Cardiomyopathy (From the NCDR((R)) Implantable Cardioverter-Defibrillator Registry). Am J Cardiol 2017;120:1891-1898.
517. Stollberger C, Blazek G, Dobias C, Hanafin A, Wegner C, Finsterer J. Frequency of stroke and embolism in left ventricular hypertrabeculation/noncompaction. Am J Cardiol 2011;108:1021-3.
518. Gage BF, Waterman AD, Shannon W, Boechler M, Rich MW, Radford MJ. Validation of clinical classification schemes for predicting stroke: results from the National Registry of Atrial Fibrillation. Jama 2001;285:2864-70.
519. Gati S, Rajani R, Carr-White GS, Chambers JB. Adult left ventricular noncompaction: reappraisal of current diagnostic imaging modalities. JACC Cardiovascular imaging 2014;7:1266-75.
520. Ivanov A, Dabiesingh DS, Bhumireddy GP et al. Prevalence and Prognostic Significance of Left Ventricular Noncompaction in Patients Referred for Cardiac Magnetic Resonance Imaging. Circulation Cardiovascular imaging 2017;10.
521. Sidhu MS, Uthamalingam S, Ahmed W et al. Defining left ventricular noncompaction using cardiac computed tomography. Journal of thoracic imaging 2014;29:60-6.
522. Kawel-Boehm N, McClelland RL, Zemrak F et al. Hypertrabeculated Left Ventricular Myocardium in Relationship to Myocardial Function and Fibrosis: The Multi-Ethnic Study of Atherosclerosis. Radiology 2017;284:667-675.
523. Chin TK, Perloff JK, Williams RG, Jue K, Mohrmann R. Isolated noncompaction of left ventricular myocardium. A study of eight cases. Circulation 1990;82:507-13.
524. Jenni R, Oechslin E, Schneider J, Attenhofer Jost C, Kaufmann PA. Echocardiographic and pathoanatomical characteristics of isolated left ventricular non-compaction: a step towards classification as a distinct cardiomyopathy. Heart 2001;86:666-71.
525. Thuny F, Jacquier A, Jop B et al. Assessment of left ventricular non-compaction in adults: side-by-side comparison of cardiac magnetic resonance imaging with echocardiography. Archives of cardiovascular diseases 2010;103:150-9.

Appendix 1. Author disclosure table

Writing group member	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
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Michael J. Ackerman, MD, PhD	Mayo Clinic, Rochester, Minnesota	0: Abbott; 0: Audentes Therapeutics; 0: Boston Scientific; 0: Gilead Sciences; 1: Invitae; 1: Medtronic; 0: MyoKardia	None	5: National Institutes of Health	None	None	None	0: AliveCor; 0: Blue Ox Healthcare; 0: StemoniX	None
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Writing group member	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
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Writing group member	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
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Writing group member	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
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Arthur A.M. Wilde, MD, PhD	University of Amsterdam, Academic Medical Center, Amsterdam, the Netherlands; Department of Medicine, Columbia University Irving Medical Center, New York, New York; European Reference Network for Rare and Low Prevalence Complex Diseases of the Heart	None	None	None	None	None	None	None	None

Writing group member	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
Wojciech Zareba, MD, PhD	University of Rochester, Rochester, New York	None	None	5: BIOTRONIK; 5: EBR Systems; 5: Gilead Sciences; 5: LivaNova	None	None	None	None	None

Number value: **0** = $0; **1** = ≤ $10,000; **2** = > $10,000 to ≤ $25,000; **3** = > $25,000 to ≤ $50,000; **4** = > $50,000 to ≤ $100,000; **5** = > $100,000.

*Research and fellowship support are classed as programmatic support. Sources of programmatic support are disclosed but are not regarded as a relevant relationship with industry for writing group members or reviewers.

Appendix 2. Reviewer disclosure table

Peer Reviewer	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
Peter Aziz, MD	Cleveland Clinic, Cleveland, Ohio	None	None	None	None	None	None	None	None
Mina K. Chung, MD, FHRS	Cleveland Clinic, Cleveland, Ohio	2: ABIM	None	5: AHA; 5: NIH	None	None		1: Elsevier; 1: UpToDate	0: ACC (EP Section Leadership Council member); 0: AHA (Chair, ECG & Arrhythmias Committee; Member, Clinical Cardiology Leadership Committee; Member, Committee on Scientific Sessions Programming); 0: Amarin (Data monitoring committee member); 0: BIOTRONIK; 2: AHA (Associate Editor, Circulation Arrhythmia & Electrophysiology)
Shriprasad Deshpande, MBBS, MS	Children's National, Washington, DC	None	None	None	None	None	None	None	None

Peer Reviewer	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
Susan Etheridge, MD, FACC	University of Utah, Salt Lake City, Utah	1: UpToDate	None	0: NIH	None	None	None	None	0: Sudden Arrhythmia Death Foundation
Marcio Jansen de Oliveira Figueiredo, MD	University of Campinas, Campinas, São Paulo, Brazil	1: Boehringer Ingelheim; 1: Daiichi-Sankyo	None	None	None	None	None	None	None
John Gorscan III, MD, FASE	Washington University School of Medicine, St. Louis, Missouri	1: EBR systems 1: V-wave, Inc.	None	2: V-wave Inc. 2: EBR Systems	None	None	None	None	None
Denise Tessariol Hachul, MD	Heart Institute, University of São Paulo, São Paulo, Brazil								
Robert Hamilton, MD	The Hospital for Sick Children, Toronto, Ontario	None	None	None	None	None	None	None	None
Richard Hauer, MD	ICIN-Netherlands Heart Institute, Utrecht, the Netherlands	None	None	None	None	None	None	None	None
Minoru Horie, MD, PhD	Shiga University of Medical Sciences, Shiga, Japan	None	None	None	None	None	None	None	None

Peer Reviewer	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
Rajesh Janardhanan, MD, MRCP, FACC, FASE	University of Arizona College of Medicine, Tucson, Arizona	None	None	None	None	None	None	None	None
Neal Lakdawala, MD	Brigham and Women's Hospital, Boston, Massachusetts	1: Array Biopharma; 1: MyoKardia	None	None	None	None	None	None	None
Andrew P. Landstrom, MD, PhD	Duke University School of Medicine, Durham, North Carolina	None	None	None	None	None	None	None	None
Andrew Martin, MBChB, CCDS	Green Lane Cardiovascular Service, Auckland, New Zealand	None	None	None	None	None	None	None	None
Ana Morales, MS	The Ohio State University, Columbus, Ohio	1: NSGC	None	4: NIH	None	None	None	None	None
Brittney Murray, MS	Johns Hopkins Hospital, Baltimore, Maryland	1: Clear Genetics; 1: My Gene Counsel; 1: PWN Health	None	None	None	None	None	None	None
Santiago Nava Townsend, MD	Departamento de Electrofisiología Cardiaca, Instituto	1: Cook Medical; 2: CORDIS – Johnson & Johnson	None	None	None	None	None	None	None

Peer Reviewer	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
	Nacional de Cardiología Ignacio Chávez, Mexico City, Mexico								
Stuart Dean Russell, MD	Duke University School of Medicine, Durham, North Carolina	1: Medtronic	None	0: Abbott Laboratories; SubQ Pharmaceuticals	None	None	None	None	None
Frederic Sacher, MD, PhD	LIRYC Institute/ Bordeaux University, Pessac, France	1: Abbott Laboratories; 1: Bayer; 1: Biosense Webster; 1: Boehringer Ingelheim; 1: Boston Scientific; 1: LivaNova; 1: Medtronic; 1: Pfizer	None	None	None	None	None	None	None
Mauricio Scanavacca, MD	Instituto Do Coracao, Sao Paulo, Brazil	None	None	None	None	None	None	None	None
Kavita Sharma, MD	Johns Hopkins University, Baltimore, Maryland	1: Novartis Pharmaceuticals Corporation	None	3: NIH; 3: AHA	None	None	None	None	None

Peer Reviewer	Employment	Honoraria/ Speaking/ Consulting	Speakers' bureau	Research*	Fellowship support*	Ownership/ Partnership /Principal/ Majority stockholder	Stock or stock options	Intellectual property/ Royalties	Other
Yoshihide Takahashi, MD	Tokyo Medical and Dental University, Tokyo, Japan	1: Abbott; 1: Biosense Webster; 1: BIOTRONIK; 1: Japan Lifeline	None	None	None	None	None	None	None
Harikrishna Tandri, MD	Johns Hopkins University, Baltimore, Maryland	1: Abbott	None	None	None	None	None	None	None
Gaurav A. Upadhyay, MD, FACC	University of Chicago Medicine, Chicago, Illinois	1: Abbott Laboratories; 1: BIOTRONIK; 1: CardioNet; 1: Medtronic; 1: ZOLL Medical Corporation	None	None	None	None	None	None	None
Christian Wolpert, MD	University Hospital Mannheim, Ludwigsburg, Germany	None	None	None	None	None	None	None	None

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NIH = National Institutes of Health; NSGC = National Society of Genetic Counselors.
*Research and fellowship support are classed as programmatic support. Sources of programmatic support are disclosed but are not regarded as a relevant relationship with industry for writing group members or reviewers.

Cascade Family Screening											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Bauce et al.	2011	21723241	Retrospective cohort	53 patients from 27 families	Desomosomal gene carriers	Clinical diagnosis	In 40 family members aged <18 at the study onset, a diagnosis was made in 9 at a mean age of 17.8 years. Disease features, specifically LV LGE was seen in others in the absence of other ECG or structural findings, including a 10-yr old.		None		
Bauce et al.	2005	15941723	Retrospective cohort	4 families with DSP mutations	Family members with clinical and genetic findings	Outcome	Sudden death in a 15-yr old with extensive inflammatory and fibrotic changes on autopsy.				
Bhonsale et al.	2015	25616645	Retrospective cohort	577 patients (347 relatives)	Documented ACM gene variants in desmosomal, TMEM-43 and PLN. 80% PKP2	Clinical outcomes by genetic variant	Patients with sudden cardiac death or ventricular fibrillaiton presented at a younger median age compared to those presenting with sustained monomorphic VT (23 versus 36 years, P<0.001). Patients with >1 mutation had sustained VT/VF at a younger age, more frequent LV dysfunction and cardiac transplantation, and desmoplakin mutation carriers had more frequent ventricular dysfunction. Missense mutation carreier had similar outcomes to those with truncating or splice site mutations and men were more likely to be probands and more severe arrhythmias.				
Charron et al.	2010	20823110	DCM clinical screening guide				Important considerations for genetic testing in asymptomatic minors. Needs multidisciplinary approach.				
Charron et al.	2018	29378019	Prospective cohort study	n=143 ARVC patients	>18 years at enrollment; informed consent; meeting diagnostic criteria for HCM, DCM, ARVC, or RCM	Description of baseline characteristics and management of registry patients	43/106 (40.6%) had positive FHx, 34/136 (25%) had positive FHx of SCD				
Dalal et al.	2006	17010805	Retrospective cohort study	64 individuals in 9 families with ARVD/C and a proband with PKP2 mutation, investigating the penetrance among mutation carriers	Probands meeting 1994 TFC, and also with PKP2 mutation; all consenting family members were included	Phenotypic manifestations and their correlation with mutation status	Among non-proband mutation-carriers, approximately 1/3 also met criteria for ARVD/C, approximately 1/3 had sub-diagnostic features of this condition, and 1/3 had normal screening evaluations.				
Fatkin et al.	1999	10580070	Retrospective cohort/gene discovery	5 families - 26 clinically affected	LMNA variant	Clinical disease outcomes: heart failure, ventricular arrhythmias and conduction disease	Disease was evident in teenager with HF and SCD. No evidence of onset <12 years with isolated/predominant cardiac disease.				

Groeneweg et al.	2015	25820315	Restrospective cohort	562 family members	Family members of proven ARVC with or without genetic findings. Median age of evaluation 35 years (range 1-87)	82% asymoptomatic; 27 (5%) presented with cardiac arrest; 207 (37%) diagnosed with ACM over study course - ventricular ectopy and TAD most frequent findings. Clinical outcomes better than probands - more evident in identified gene carriers than those without. 6 died (4 SCD and 2 HF).	No specific mention of <18 years				
Hamid et al.	2002	12392835	Consecutive patient series (single time point)	n=298 first and second degree relatives	First or second degree relative where proband met TFC, who underwent cardiac evaluation in a specialist clinic	ARVC by TFC, DCM	Of 298 relatives, 29 (10%) had ARVC on family screening. There were 19/67 families with familial disease (28%). 72% of affected relatives were asymptomatic, 17% had VT and 21% LV involvement. Further 32 (11%) relative had non-diagnostic changes (ECG, echo, holter). 4 fulfilled diagnostic criteria for DCM.				
Hasselberg et al.	2018	29095976	Retrospective cohort	35 probands and 93 family members with LMNA variant identified from familial DCM clinic	LMNA variant	Clinical disease outcomes: heart failure, ventricular arrhythmias and conduction disease	Asymptomatic LMNA genotype-positive family members (age 31 ± 15 years) had a 9% annual incidence of a newly documented cardiac phenotype and 61% (19/31) of cardiac penetrance during 4.4 ± 2.9 years of follow-up.				
Hodgkinson et al.	2013	22725725	Restrospective cohort	412 subjects: 258 affected and 154 unaffacted	TMEM-43 S358L carriers	Clinical outcomes: sudden death, heart failure and transplantation	Males more severely affected than females. Earliest clinical feature is >200 PVCs on Holter - males (25 yrs) and females (48 yrs). No clinical features evident <10 years.				
Laurent et al.	2012	22766342	Restrospective cohort	3 unrelated families - 21 individuals	Carriers of SCN5A R222Q variant - clinically defined as multifocal ectopic purkinje-related contractions (MEPPC)	Clinical outcomes: DCM, atrial arrhythmias and SCD. Beneficial effect on ectopy burden and LV function seen with hydroquinidine.	Disease expression evident in chidren <10 years of age, including SCD aged 11. One further infant SCD in one family with no clinical or genetic data available.				
Ortiz-Genga et al.	2016	27908349	Restrospective cohort	28 probands and 121 relatives	Carriers of FLNC truncating mutations	Clinical outcomes of sudden death, appropriate defibrillator shock, heart failuredeath or cardiac transplantation	12 carriers with cardiac arrest, and was first manifestation of disease in 4. 5 carriers underwent heart transplantation. 40 sudden deaths in 21 of 28 families. SCD in 17 year old proband - father carried same mutation. HTx in 1 year old proband - mother and sister carried same mutation.				
Otten et al.	2010	20423733	Restrospective cohort	2 Dutch families with DES variants		Clinical outcomes: severe biventricular ACM. Desmin aggregates on histology with decreased DSP and PKP2 at intercalated discs	Disease evidence in teenagers - no evidence prior to 12 years.				

Perrin et al.	2013	23810883	Age-matched cohort	N=30 asymptomatic ARVC gene carriers compared to 30 healthy controls. A second group of 25 ARVC patients with history of VT were compared	ARVC gene carriers, healthy controls, ARVC patients with VT		Compared to healthy controls, ARVC gene carriers developed during exercise stress testing more frequently: epsilon waves (14% vs 0, p=0.048), premature ventricular contractions (57% vs 10%, p=0.0003 with superior axis only seen in gene cariers), new QRS terminal activation duration of at least 55 ms (32% vs 7%, p=0.03). ARVC patients with history of sustained ventricular arrhythmia or cardiac arrest showed during exercise stress testing new epsilon waves (17%), superior axis premature ventricular contractions (84%) and new terminal activation duration of at least 55 ms in 67%.	Exercise stress testing unmasks an electrical substrate in ARVC gene carriers and is useful in evaluation and prognostic decisions.			
Protonotarios et al.	2016	25825460	Retrospective cohort study (serial 6-12 month evaluations). They also performed a sub-study, an age-matched case control study to investigate ECG/echo characteristics at baseline (cases= carriers with arrhythmic risk and controls= carriers with no event).	n=105 desmosome gene carriers from 39 consecutive families, includes probands and relatives. N=30 did not meet TFC (relatives)	Proband 2010 TFC. Attending one of 3 specialist centers	First major arrhythmic event; spontaneous sustained VT and SCD including resuscitated cardiac arrest	n=43 (41%) gene carriers experienced a major arrhythmic event. 70% were male, 67% were probands and all had ARVC. PPV and NPV of the TFC for occurance of arrhythmic events was 57% and 100% - suggesting mutation carriers with incomplete or no phenotype according to TFC are at very low risk.	Mutation carriers who do not fulfil TFC are at very low risk of arrhythmic events.		30/105 were homozygous JUP carriers (Naxos), but models accounted for this.	
te Riele et al.	2014	25034067	Retrospective cohort study (baseline and follow-up time points)	n=117 relatives from 64 families. N=84 were gene positive carriers, n=33 were first-degree relatives where proband had indeterminate genetic testing	Probands meeting 2010 TFC, undergone 5 gene testing. Sought from ARVC Registry	ARVC by 2010 TFC	43/117 fulfilled TFC at baseline evaluation. 37 relatives had complete baseline and follow-up investigations (mean 4.1 ± 2.3 years follow-up time). Holter/SAECG changes occurred in 27% whereas structural changes were only seen in 1/37. No relatives who did not meet TFC had arrhythmic events during the follow-up period.	Good prognosis for ARVC relatives that do not meet 2010 TFC and little chance of structural progression. Family evaluation may be better focused on electrical abnormalities.			
te Riele et al.	2016	26314686	Restrospectiv e cohort	n=274 relatives from 138 families		No diagnosis was made prior to 14 years of age. OR of diagnosis <18 years 0.37 (0.14-0.93). Majority of diagnoses made after the age of 20 yrs.	One family member had electrical, structural and arrhythmic features, suggesting very low penetrance in those <20 years, but not impossible.				

van Rijsingen et al.	2014	24909667	Retrospective cohort	403 patients (83 families with 1-14 family members)	Carriers of Dutch founder variant - PLN R14del		The youngest age at which a malignant ventricular arrhythmia occurred was 20 years, whereas for an end-stage heart failure event this was 31 years. No disease onset prior to 15 years.				
van Tintelen et al.	2009	19879535	Restrospective cohort	27 patients from 5 families	DES S13F variant	Evidence of AV block and RV disease at a young age	Disease evident in teenagers (14 years with ECG abnormalities, structural heart disease and syncope)-no evidence prior to 12 years.				
Quarta G et al.	2011	21606390	Retrospective cohort	210 first-degree and 45 second-degree relatives from 100 families.	Families and probands with ARVC.	Expression of clinical disease, cardiovascular events: sudden death, death from heart failure or stroke, heart transplantation.	Living probands had more severe disease than relatives. Causal mutations in 58% of families and 73% of living probands, and 28% had another desmosomal variant. 93 relatives had a causal mutation with 33% meeting 2010 Task force criteria compared to 19% satisfiying the 1994 Task Force criteria (P=0.03). Another desmosomal gene variant seen in 10% associated with a 5 times increased risk of developing disease (OR 4.7, P=0.04).	Marked intrafamilial phenotype diversity and penetrance greater with 2010 Task Force criteria. Relatives with more than 1 genetic variant had higher risk of developing clinical disease.			

ACM = arrhythmogenic cardiomyopathy; ARVC = arrhythmogenic right ventricular cardiomyopathy; ARVD = arrhythmogenic right ventricular dysplasia; DCM = dilated cardiomyopathy; ECG = electrocardiogram; FHx = family history; HCM = hypertrophic cardiomyopathy; HF = heart failure;

Electrocardiogram											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Ainsworth et al.	2006	16567288	Case control	20 pts with ARVC, 24 RVOT-VT		Mean QRS duration, frontal plane axis, and precordial R-wave transition were measured in 12-lead ECGs recorded during VT	QRS duration is longer in ARVC compared with RVOT VT	Lead I QRS duration 120 ms had a sensitivity of 100%, specificity 46%, positive predictive value 61%, and negative predictive value 100% for ARVC. The addition of mean QRS axis 30° (R S in lead III) to the above criterion increased specificity for ARVC to 100%.		Small sample size	
Batchvarov et al.	2016	26622053	Case control	44 pts with ARVC, 276 healthy subjects, 36 genotyped ARVC families	TFC in 1994, 2010	The length and area of the terminal S wave in V1 to V3 were measured automatically. T wave negativity was assessed in V1 to V6 and in the bipolar chest (CF) leads computed from the standard 12 leads.	The terminal S wave length and area in the right precordial leads are diagnostically useful and suitable for automatic analysis in ARVC. The bipolar chest leads are diagnostically superior to the unipolar precordial leads.	The length and area of the terminal S wave were significantly shorter, whereas the S wave duration was significantly longer in ARVC patients compared with matched controls. Among members of ARVC families, those with mutations (n=15) had shorter QRS length in V2 and V3 and smaller QRS area in lead V2 compared with those without mutations (n=20). S wave duration in V1.48 ms or major T wave negativity in CF leads separated ARVC patients from matched controls with 90% sensitivity and 86% specificity.		No analysis in the pts with RBBB.	
Cortez et al.	2017	29029613	Case control	155 pts with ARVC TFC 2010	ECG(-) not fullfill TFC depolarization/repolarization age and gender-matched control subjects	Electrocardiogram measures of a 3-dimentional spatial QRS-T angle, a right-precordial-directed orthogonal QRS-T (RPD) angle, a root mean square of the right sided depolarizing forces (RtRMS-QRS), QRS duration (QRSd) and the corrected QT interval (QTc), and a measured angle including the upslope and downslope of the S-wave (S-wave angle) were assessed.	Right-sided VCG or measured angle were better markers than the spatial QRS-T angle, the QRSd or QTc, in the absence of Taskforce ECG criteria.	ECG(-) ARVD/C patients (66 patients) were compared to 66 control patients (41.7 ± 17.6 years, 65.2% male). All parameters tested except the QRSd and QTc significantly differentiated -ECG ARVD/C from control patients ($p < 0.004$ to $p < 0.001$). The RPD angle and RtRMS-QRS best differentiated the groups. Combined, the 2 novel criteria gave 81.8% sensitivity, 90.9% specificity and odds ratio of 45.0 (95% confidence interval 15.8 to 128.2).			
Cox et al.	2008	18373594	Case control	42 pts with ARVC, 27 control RVOT-VT	TFC in 1994	(a) Prolonged terminal activation duration, an indicator of activation delay; (b) VT with LBBB morphology and superior axis; and (c) multiple different VT morphologies	Additional criteria (a), (b), (c) were specific for ARVD/C and more sensitive than the current TFC.	(a) 30 (71%) 28, (b) 28 (67%), and (c) 37 (88%) in ARVC, (a) 1 (4%), (b) 1 (4%), (c) 1 (4%) in controls	Student's t-test (a) $p<0.001$, (b) $p<0.001$, (c) $p<0.001$	Small numbers	

Gaido et al.	2017	28283360	Case series	3 cases belonging to the same family		Demographic data, presenting complaints, cardiac findings, electrocardiography, echocardiography, cardiac magnetic resonance (CMR) results and treatment data were collected. The genetic analysis evaluated 174 genes associated with cardiovascular disease.	ARVC may lead to an extreme phenotypic variability in clinical manifestations even within patients coming from the same family in which ARVC is caused by the same genetic mutation. ECG changes reflect the disease progression demonstrated by imaging and may precede wall motion abnormalities by years.	Case 1 showed a clear RV involvement with typical ECG signs of RV involvement. Case 2 had ECG signs of a clear LV involvement, in particular the progressive evolution to a QS morphology in left precordial leads together with left epsilon wave appearance (rarely reported). Imaging analysis in this patient showed a clear biventricular involvement with biventricular reduced ejection fraction. Case 3 was referred with imaging tests suggestive for only RV involvement, but ECG showed a progression to rS in left precordial leads suggestive for LV involvement.			
Jain et al.	2009	19635971	Case control	100 pts with ARVC, 57 controls	TFC in 1994	Right precordial TWI through V2, V3, V4 TWI in inferior leads (2 of 3) Epsilon wave QRS prolongation in right precordial leads QRS > 110ms Parietal block Prolonged TAD Increased ratio in QRSd of the right vs left precordial leads R'/s ratio<1	In the absence of a CRBBB or IRBBB, TWI through V3 is the single ECG parameter that demonstrates optimal sensitivity and specificity. IRBBB pattern, TWI through V3 is also the single ECG parameter that demonstrates optimal sensitivity and specificity. CRBBB pattern, an r/s ratio 1 in V1 was the single ECG parameter that demonstrates optimal sensitivity and specificity.				
Malhotra et al.	2017	28057231					Anterior T-wave inversion confined to leads V1 to V2 is a normal variant or physiological phenomenon in asymptomatic white individuals without a relevant family history. Anterior T-wave inversion beyond V2 is rare, TWI extending beyond V2 is present in only 1% of females and 0.2% in men and may justify further evaluation in white individuals.				
Marcus	2005	15842973	Case	161 healthy young subjects	Healthy young subjects 5-45y/o	Percentage of T-wave inversion in precordial leads V1 to V3	T-wave inversion in precordial leads V1 to V3 is present in <3% of apparently healthy subjects who are 19 to 45 years of age				
Morin et al.	2010	20538137	Multicenter registry	79 pts with ARVC and 121 pts with RVOT-tachy			The presence of TWI in electrocardiographic leads V1 to V3 supports the diagnosis of ARVC.	During sinus rhythm, 37 patients (47%) with ARVC and 5 patients (4%) with RVOT tachycardia had TWI in leads V(1) to V(3). For the diagnosis of ARVC, TWI in leads V(1) to V(3) had sensitivity of 47% and specificity of 96%. TWI in leads V(1) to V(4) had sensitivity of 32% and specificity of 98%.			

Novak et al.	2017	28431055	Case control	20 desmosomal gene mutation carriers with no or mild ARVC phenotype; 33 age- and sex-matched subjects with idiopathic RVOT arrhythmias		All patients exhibited isolated monomorphic ventricular ectopic beats with LBBB/inferior axis morphology. The predictive value of ectopic QRS morphology and coupling interval was evaluated.	The morphology of the QRS in the two conditions may help differential diagnosis, and features such as ectopic QRS axis .908 (negative QRS polarity in lead 1), intrinsicoid deflection time .80 ms, and QS morphology in lead V1, particularly when present in combination, should raise high clinical suspicion of an underlying cardiomyopathy when evaluating patients with apparently idiopathic RVOT VEBs to prompt more in-depth clinical evaluation.	(1) maximal QRS duration >160 ms (60 vs. 27%, P = 0.02), (2) intrinsicoid deflection time >80 ms (65 vs. 24%, P = 0.01), (3) initial QRS slurring (40 vs. 12%, P = 0.04), (4) QS pattern in lead V1 (90 vs. 36%, P < 0.001), (5) QRS axis >90° in limb leads (60 vs. 24%, P = 0.01) were more common in desmosomal-gene mutation carriers ARVC. Intrinsicoid deflection time >80 ms [odds ratio (OR) = 9.9], QS pattern in lead V1 (OR = 28), and QRS axis >90° (OR = 5.7) remained independent predictors of early ARVC.			
Platonov et al.	2016	26304715	Cohort	ECG tracings depicting leads V1, V2, and V3 collected from individuals evaluated for ARVC/D (n = 30) were given to panel members who were asked to respond to the question whether ECG patterns meet epsilon wave definition outlined by the TFC 2010	Patients with ARVC and family members screened for ARVC from the Nordic ARVC registry (n=21) and high resolution ECG examples from the literature (n=9).	Evaluation of interobserver agreement for assessment of an epsilon wave. Secondary analysis of importance of epsilon wave for an ARVC diagnosis among n=105 patients identified in registries who met diagnostic criteria for definite ARVC by 2010 Task Force Criteria.	Interobserver variability in the assessment of epsilon waves is high; however, the impact of epsilon waves on ARVC/D diagnosis is negligibly low. The results urge caution in the assessment of epsilon waves, especially in patients who would not otherwise meet diagnostic criteria.	The number of ECG patterns identified as epsilon waves varied from 5 to 18 per reviewer (median 13 per reviewer). A unanimous agreement was reached for only 10 cases (33%), 2 of which qualified as epsilon waves and 8 as non-epsilon waves by all panel members. Among 105 definite ARVC patients with an epsilon wave, 104 would still be characterized as definite without counting the epsilon wave.			
Tanawuttiwat et al.	2016	26757204	Cohort	30 pts with ARVC	TFC in 2010	Twelve-lead ECGs were classified into 5 patterns: (1) normal QRS (11 patients); (2) terminal activation delay (TAD) (3 patients); (3) incomplete right bundle branch block (IRBBB) (5 patients); (4) epsilon wave (5 patients); (5) complete right bundle branch block (CRBBB) (6 patients). Epi/endocardial mapping	Epsilon waves are often associated with severe conduction delay and extensive endocardial scarring in addition to epicardial disease. The timing of epsilon waves on surface ECG correlated with electrical activation of the subtricuspid region.	Timing of local ventricular activation and extent of scar was then correlated with surface QRS. Earliest endocardial and epicardial RV activation occurred on the mid anteroseptal wall in all patients despite the CRBBB pattern on ECG. Total RV activation times increased from normal QRS to prolonged TAD, IRBBB, epsilon wave, and CRBBB, respectively (103.9 ± 5.6, 116.3 ± 6.5, 117.8 ± 2.7, 146.4 ± 16.3, and 154.3 ± 6.3, respectively, P < 0.05). The total epicardial scar area (cm2) was similar among the different ECG patterns. Median endocardial scar burden was significantly higher in patients with epsilon waves even compared with patients with CRBBB (34.3 vs. 11.3 cm2, P < 0.01). Timing of epsilon wave corresponded to activation of the subtricuspid region in all patients.			

te Riele et al.	2013	23816439	Case control	145 pts with ARVC 2010 TFC	(ECG normal 17 pts, abnormal: ECG TFC ≥1: 128 pts) TFC	Cardiologic investigations within 6 months of the event were evaluated as per TFC in those with a nonspecific or normal ECG.	Patients with a nonspecific or normal ECG had alternative evidence of disease expression. We are not to rely exclusively on ECG in ARVD/C, but to assess arrhythmic risk by comprehensive clinical evaluation.	Mean age of these patients was 41.3 ± 12.4 years and 14 (82%) were men, comparable to those with an abnormal ECG. Most patients with a nonspecific or normal ECG showed ≥1 TFC on Holter monitoring (n = 9 of 10) and signal-averaged ECG (n = 4 of 5), and all had nonsustained ventricular tachycardia recorded. Among 15 patients who underwent structural evaluation, 11 (73%) showed structural TFC (9 major and 2 minor).			
Khurram et. al.	2004	15381658	Case control	50 pts with ARVC, 50 control, 28 RVOT VT	TFC in 1994	ECG parameters that best distinguish ARVC from controls. Parameters studied: T-wave inversion in V1-V3, Epsilon wave, QRSduration, S-wave upstroke 55ms	A prolonged S-wave upstroke in V1 through V3 is the most frequent ECG finding in ARVD/C.	T-wave inversion V1–V3 33 (85%) 0 (—) 0(—) Epsilon wave 13 (33%) 0 (—) 0(—) QRSd 110 ms in V1–V3 25 (64%) 0 (—) 0(—) S-wave upstroke 55 ms V1–V3 37 (95%) 1 (7%) 1 (2%)	Student's t test p<0.0001	Interindividual variation in lead placement and day-to-day variation in voltages can result in variations in ECG pattern.	
Kamath et al.	2011	20933608	Case control	N=98 ARVC probands diagnosed as affected or borderline compared to N=103 controls	ARVC patients diagnosed by TFC in 1994	SAECG abnormalities in relation to diagnosis of ARVC and association with clinical presentiation of ventricular arrhythmias. The vector magnitude composite was analyzed for fQRS duration, low amplitude signal duration below 40 μV (LAS) and root mean square voltage in last 40 ms of the QRS (RMS40). Receiver operator curves (ROC) were plotted to determine the value of using SAECG parameters for diagnosis of ARVD/C	SAECG was a powerful diagnostic test. In particular, fQRS duration may warrant additional weighting in formal diagnostic criteria.	Each SAECG parameter was highly associated with the diagnosis of ARVD/C: fQRS (area under curve [AUC] = 0.86; p <0.0001) (see Figure), LAS (AUC = 0.87; p < 0.0001) and RMS40 (AUC = 0.83; p < 0.0001). Of the 3 parameters, fQRS >108 ms provided optimal sensitivity (74%) and specificity (91%) and was superior to LAS > 38 ms (sensitivity 65%/specificity 92%) and RMS40 < 50 μV (sensitivity 43%/specificity 91%) for the diagnosis of ARVD/C			

ARVC = arrhythmogenic right ventricular cardiomyopathy; ARVD = arrhythmogenic right ventricular dysplasia; AUC = area under curve; CMR = cardiac magnetic resonance; CRBBB = complete right bundle branch block; ECG = electrocardiogram; IRBBB = incomplete right bundle branch block;

Risk Stratification and ICD Decisions											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Anselme et al.	2013	23811080	Registry	47	LAMIN A/C	VT/VF	Univariate predictor: Conduction disease HR: 5.20 (1.14–23.53) P =03				
Bänsch et al.	2002	11914254	RCT		LVEF ≤ 30%, and recent onset of cardiomyopathy ≤ 9 months, randomized to ICD or control	Primary end point: all cause mortality at 1 year	Trial stopped after inclusion of 104 patients as all cause mortality rate at 1 year was not as expected (30%) in the control group. Mean follow up was 22.8 ± 4.3 months. After 1 year 4 patients in the ICD group and 2 in the control group had died, no sudden death in the first and second year. At a follow up of 5.5 ± 2.2 years, 13 deaths in ICD group, 17 in control, with no difference in cumulative survival.		Kaplan-Meier survival analysis		
Bardy et al.	2005	15659722	RCT	2521 patients, randomized to conventional therapy plus placebo, versus amiodarone, versus ICD	LVEF ≤ 35%, NYHA II or III	Death from any cause	Median LVEF 25%, 48% non ischemic cardiomyopathy. Compared to placebo, amiodarone had similar risk of death, ICD therapy associated with decreased risk of death with HR of 0.77, P=0.007 and absolute mortality decrease of 7.2 percentage points after 5 years.	Results did not vary by etiology of heart failure (ischemic versus non-ischemic).	Cumulative mortality assessed by Kaplan-Meier method, with differences between treatment groups assessed by log-rank test, adjusted for NYHA class and cause of heart failure. Relative risks determined from Cox proportional-hazards.	Unknown what percent of non-ischemic population was diagnosed with ACM.	
Bristow et al.	2004	15152059	RCT	1520 patients randomized to medical therapy alone or in combination with cardiac resynchronization therapy (CRT) with pacemaker or defibrillator.	NYHA III or IV, QRS > 120ms	Time to death or hospitalization for any cause	CRT with pacemaker decreased primary end point with HR of 0.81 p=0.014, CRT with defibrillator as well with HR of 0.80 p=0.01. CRT with defibrillator reduced risk of death by 36% (P=0.003)	CRT reduced combined risk of death from any cause or first hospitalization and when with defibrillator also reduced mortality. CRT reduced the primary end point in patients with both ischemic and non-ischemic cardiomyopathy.	Kaplan-Meier analysis with log-rank test to assess differences between groups.	Unknown what percent of non-ischemic population was diagnosed with ACM.	
Corrado et al.	2010	20823389	Registry	106	ARVC-ICD no prior arrhythmias	VF/VFL. Combination of VT/V	Univariate predictor of VF/VFL included: Syncope HR: 4.36 (2.86 –7.91) p= 0.001. Multivariate predictor of VF/VFL included Syncope HR: 3.16 (1.39 –5.63) p= 0.005. Univariate predictor of combination of VT/VF/ICD shock included: Syncope HR: 3.82 (2.15–5.72) p=0.008, NSVT HR: 1.74 (1.35–3.19) p=0.03, Age < 35 y HR: 1.36 (0.91–3.13) p=0.07. Multivariate predictor of combination of VT/VF/ICD shock included Syncope HR: 2.94 (1.83–4.67) p=0.013, NSVT HR: 1.62 (0.96–4.62) p=0.068.				

Corrado et al.	2003	14638546	Registry	132	ARVC-ICD	VF/VFL	Multivariate predictors included: Age per 5-year interval HR: 0.77 (0.57–0.96) p=0.007, Left ventricular ejection fraction HR: 0.94 (0.89–0.95) p=0.037, Cardiac arrest HR: 79 (6.8–90.6) p<0.001, VT with hemodynamic compromise HR: 14 (1.7–21.1) p=0.015, Syncope unexplained HR: 7.5 (0.84–1.81) p=0.07				
Desai et al.	2004	15598919	Meta-analysis of RCTs	8 trials enrolling a total of 2146 patients with non-ischemic cardiomyopathy	Prospective RCTs of ICD or combined CRT-D versus medical therapy that enrolled at least some indivuduals that had a non-ischemic cardiomypathy, and reported all cause mortality as an outcome	All cause mortality	5 primary prevention trials (n=1854 patients) with total mortality reduction in patients randomized to an ICD or CRT-D versus medical therapy with risk ratio of 0.69, p=0.002, and remained significant when excluded CRT-D. Secondary prevention trials (2 of 3 that gave subgroup estimates, n=256 patients with non ischemic cardiomyopathy) showed non significant mortality reduction with ICD therapy. Analysis of all 7 trials showed 31% reduction in mortality with an ICD (relative risk 0.69, p=0.002). Primary prevention trials: CAT, AMIOVIRT, DEFINITE, SCD-HeFT, COMPANION. Secondary prevention trials: AVID, CASH, CIDS	ICD therapy reduces mortality in patients with non-ischemic cardiomyopathy in this meta analysis		Unknown what percent of non-ischemic population was diagnosed with ACM.	
Hasselberg et al.	2018	29095976	Registry	79	LAMIN A/C	VT/VF	Univariate predicators: Atrioventricular block p=0.03, Ejection fraction <45% p<0.05				
Hodgkinson et al.	2005	15680719	Cohort - ICD patients to matched control	11 families with 197 at high risk	ARVC (Newfoundland cohort) with any of these high risk features: sustained VT, unexplained sudden cardiac death < 50 years, high risk DNA haplotype, obligate carrier status by pedigree analysis.	Primary outcome all cause mortality. Secondary outcomes: time to iniital appropirate ICD discharge for sustained VT, time to first VT> 240 bpm	Among high risk subjects, 50% of males dead by age 39, and females by age 71, with relative risk of death of 5.1 (95% CI 3-8.5) in males. Five year mortality in males with an ICD was zero, vs 28% in controls (p=0.009). Within 5 years, ICD had discharged for VT in 70% and for VT> 240 bpm in 30%. There was no difference in ICD discharge rate according to ICD indication (primary versus secondary prevention)	High mortality in this patient group for which those at high risk had improved survival with an ICD			
Hoorntje et al.	2017	28790152	Registry	58	LAMIN A/C	ICD shock/SCD/OHT/LVAD/D	Other than LMNA p.(Arg331Gln) mutation carriers *P* <0.001				
Hulot et al.	2004	15451782	Registry	130	ARVC	CV death/OHT	Univariate predictors included: Syncope HR: 3.51 (1.34–9.17) p=0.01, Atypical chest pain HR: 3.06 (1.16–8.02) p=0.02, RV failure HR: 10.99 (2.40–50.73) p=0.002, VT Inaugural HR: 3.04 (1.16–7.93) p=0.02, VT Recurrence HR: 2.69 (1.03–7.05) p=0.04, LV dysfunction HR: 10.64 (3.02–37.03) p=0.002. Multivariate predictors included: RV failure HR: 13.70 (2.58–71.42) p=0.002, LV dysfunction HR: 10.87 (2.84–41.7) p=0.0005				

Kadish et al.	2004	15152060	RCT	458 patients with non ischemic cardiomyopathy, randomized to medical therapy alone or to medical therapy with an ICD	Non ischemic dilated cardiomyopathy, LVEF<36% and PVCs or non sustained VT	Primary endpoint was death from any cause. Secondary end point was sudden death from arrhythmia.	Mean follow up of 29.0 ± 14.4 months, mean LVEF=21%. NYHA I- 99 patients, II - 263 patients, III - 96 patients. Mortality: HR of 0.65 benefiting ICD but not significant P=0.08. Mortality at 2 years 14.1% in standard therapy and 7.9% in ICD group. Sudden death: 3 in ICD compared to 14 in standard therapy with HR of 0.20 P=0.006	ICD reduced sudden death from arrhythmia but risk of death from any cause was nonsignificantly reduced by an ICD	Kaplan-Meier survival analysis with Cox proportional-hazards to adjust for covariates and assess hazard ratios. Analysis by intention to treat	Unknown what percent of non-ischemic population was diagnosed with ACM	
Kimura et al.	2016	29759574	Registry	110	ARVC	VT/VF/ICD shock		Univariate predictors included: Age at diagnosis, yrs HR: 0.90 (0.88–0.92) p <0.0001, Male HR 1.93 (1.14–3.50) p= 0.01. Multivariate predictors included: Age at diagnosis, yrs HR: 0.89 (0.87–0.91) p<0.0001, Male HR: 3.21 (1.84–5.97) p <0.0001.			
Kumar et al.	2016	27884249	Registry	122	LAMIN A/C	VT/VF/ICD shock	Multivariate predictors: Male sex HR: 3.2 (1.3 to 8.0) p=0.01, LVEF < 50% at first clinical contact. HR: 3.4 (1.5 to 8.1) p=0.004, nonmissense mutations HR: 2.5 (1.1 to 6.0) p=0.03				
Link et al.	2014	25011714	Registry	108	ARVC-ICD	Ventricular fibrillation or ventricular flutter treated by ICD. Combination of ventricular fibrillation or ventricular flutter treated by ICD. Ventricular tachycardia treated by ICD	Univariate predictors of VF/VFL included: younger age at enrollment P=0.032. Arrhythmic events (VT/VF) before enrollment P=0.020. Multivariate predictors of VF/VFL included: younger age at the time of ICD implant (p=0.032). Univariate predictors of VT/VF/ICD shock included: Arrhythmic events (VT/VF) before enrollment p<0.001, Syncope or VT/VF before enrollment p<0.001, LVEF LOWER (%) by MRI, p=0.009, Negative T-wave in leads II, III, aVF p=0.001, Antiarrhythmic drug treatment P<0.001. Multivariate predictors of VT/VF/ICD shock included: SMVT or SPVF preimplant (p=0.0029)				

Mazzanti et al.	2016	27931611	Registry	301	ARVC	SCD, aborted SCD, syncopal VT or electrical storm, or cardiovascular mortality		Univariable predictors included: Male sex. HR 2.76 (1.37–5.56) p=0.005, Atrial fibrillation HR: 3.51 (1.38–8.93) p=0.008, History of syncope HR: 4.54 (2.48–8.34) p<0.001, MMVT-hemodynamically tolerated. HR 3.37 (1.87–6.07) p<0.001, Participation in strenuous exercise HR:2.90 (1.14–7.38) p=0.026, Age at presentation 21–40 yrs vs. >40 yrs HR: 2.91 (1.51–5.58) p=0.001, Proband status HR: 3.54 (1.65–7.59) p=0.001. Multivariable predictors included: Male sex. HR 2.49 (1.22–5.07) p=0.012, Atrial fibrillation HR: 4.38 (1.70–11.29) p=0.002, History of syncope HR: 3.36 (1.71–6.60) p<0.001, MMVT-hemodynamically tolerated. HR: 2.19 (1.12–4.32) p=0.023, Participation in strenuous exercise HR: 2.98 (1.12–7.90) p=0.028.			
Orgeron et al.	2017	28588093	Registry	312	ARVC and ICD	Ventricular fibrillation or ventricular flutter treated by ICD. Ventricular tachycardia treated by ICD		Univariate predictors of VF/VFL included: PVC ≥1000 per 24 hours (HR, 4.39; 95% CI, 1.32–14.61; P=0.016), syncope (HR, 1.85; 95% CI, 1.10–3.11; P=0.021), age ≤30 years at presentation (HR, 1.76; 95% CI, 1.04–3.00; P<0.036), male sex (HR, 1.73; 95% CI, 1.01– 2.97; P=0.046). Univariate predictors of VT included: VT at presentation (HR:, 1.86; 95% CI 1.38–2.49; P<0.001), EPS inducibility; HR: 3.14 95% CI 1.95-5.05; P<0.001, male sex: HR: 1.62; 95% ci 1.20-2.19; P=0.001, inverted T waves in ≥3 precordial leads (HR, 1.66; 95% CI, 1.09–2.52; P=0.018), PVC count ≥1000 per 24 hours (HR, 2.30; 95% CI, 1.32–4.00; P=0.003). Multivariate predictors of VF/VFL included younger age at presentation (HR, 3.14; 95% CI, 1.32–7.48; P=0.010, high PVC frequency (HR, 4.43; 95% CI, 1.35–14.57; P<0.014). Multivariate predictors of VT included: inducibility at EPS (HR, 2.28; 95% CI, 1.10–4.70; P=0.025)			
Ortiz-Genga et al.	2016	27908349	Registry	54	FLNC Mutations	SCD/Aborted SCD	12 of 54 with SCD, LVEF mean 39%, range 21-54%				
Pasotti et al.	2008	18926329	Registry	94	LAMIN A/C	VT/VF/ICD shock	Univariate predictors: Phenotype (esp AVB and VT/VF) p=0.00001, Competitive sport p=0.0005				

Pinamonti et al.	2011	21362707	Registry	96	ARVC	CV DEATH/OHT	Univariate predictors included: No syncope p=0.04, heart failure symptoms p=0.02, NYHA III–IV p=0.03, Low-voltage QRS p=0.05, Epsilon waves p=0.007, Exercise frequent PVB p=0.04, RV aneurysm on MRI p=0.05, Amiodarone p=0.002, Severe RV dysfunction p=0.006, LVEF lower p=0.001, Significant tricuspid regurgitation p=0.004. Multivariate predictors included: Amiodarone HR: 3.72 (1.43–9.67) p=0.007, RV/LV dysfunction HR: 6.3; (2.17–17.45) P , 0.001, Significant tricuspid regurgitation HR: 5.09 (1.86–13.93) p=0.001			No analysis of arrhythmic endpoint only	
Roguin et al.	2004	15145110	Registry	42	ARVC-ICD	VT/VF/ICD shock	Univariate predictors included: Male gender 20/22 (91) 2/22 (9) 0.04, moderate-severe dilation 13 (39) 0 (0) 0.013, Spontaneous arrhythmias 23 (70) 1 (11) 0.001, Ventricular arrhythmia induction during EPS 27 (81) 4 (44) 0.024			Patients likely included in 2017 manuscript	
Strickberger et al.	2003	12767651	RCT	103 patients with nonischemic cardiomyopathy randomized to amiodarone versus ICD	Non ischemic cardiomyopathy and nonsustained VT	Primary endpoint: total mortality. Secondary endpoints: arrhythmia-free survival, quality of life and costs	Trial stopped due to futility	Mortality and quality of life in patients with nonischemic cardiomyopathy and non sustained VT treated with amidoarone or ICD were not statistically different. A trend was seen for a better cost profile and arrhythmia free survival with amiodarone			
van der Zwaag et al.	2012	22820313	Registry	97 ARVC (12 with R14del) 257 DCM (39 with R14del)	Phospholamben R14 del	VT/VF/ICD shock	In DCM pts, R14del more likely to have appropriate ICD therapy (47% to 10%, p=0.001); similar pattern in ARVC, but not significant				
van Rijsingen et al.	2014	24909667	Registry	295	Phospholamben carriers	Malignant arrhythmias	Univariate predictors include: LVEF < 45%; p<0.001, VT or NSVT; p<0.001, and BP response: p=0.006, Holter > 500 pvcs/24 hrs; p=0.019, Repolarization abn: p=0.031, Low-voltage QRS p=0.035, LVEF < 35%; p=0.045, FMH SCD; p=0.047 Multivariate predictors: LVEF < 45%; p<0.001, VT or NSVT; p<0.001				
van Rijsingen et al.	2012	22281253	Registry	269	LAMIN A/C	VT/VF/ICD shock	Univariate predictors: Nonsustained VT on Holter monitoring p<0.001, LVEF < 45% p=0.001, Male Sex p<0.001, LV enlargement p<0.001, Probands p=0.041, Atrial tachyarrhythmias p=0.049. Multivariate predictors: Nonsustained VT on Holter monitoring HR: 4.4 (1.9–10.4) p=0.003, LVEF < 45% HR: 4.4 (1.7–11.0) p=0.021, Male Sex HR: 2.9 (1.2–7.0) p=0.030				

Wichter et al.	2004	15007002	Registry	60	ARVC-ICD	VT/VF/ICD shock	Multivariate predictors included: RV dysfunction OR, 2.09 (1.03 to 4.24) p=0.041				

ACM = arrhythmogenic cardiomyopathy; ARVC = arrhythmogenic right ventricular cardiomyopathy; AVB = atrioventricular block; BP = blood pressure; CI = confidence interval; CRT-D = cardiac resynchronization therapy and defibrillator; CV = conduction velocity; EPS = electrophysiology

Medical therapy for Ventricular Arrhythmia and Dysfunction											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Connolly et al.	2006	16403928	RCT	412 patients randomized to 1 year of treatment with amiodarone plus beta blocker, sotalol alone or a beta blocker alone	Patients with an ICD and inducible or spontaneous VT or VF	ICD shock for any reason	Primary endpoint occurred in 41 beta blocker, 26 sotalol, and 12 amiodarone with beta blocker patients	Amiodarone plus beta blocker reduced risk of shock compared to beta blocker alone (HR 0.27 p<0.001) and compared to sotalol (HR 0.43, p=0.02). There was a trend to reduce shocks with sotalol compared to a beta blocker (HR 0.61, p=0.055). Adverse events seen more commonly in amiodarone patients.			While amiodarone plus a beta blocker was more effective, this was associated with more pulmonary, thyroid and symptomatic bradycardia adverse effects.
Ermakov et al.	2017	27939893	Retrospective analysis of ARVC cohort	N=8 ARVC patients	Treatment with flecainide in combination with sotalol/metoprolol after failing of single agent therapy and/or ablation	Description of arrhythmic outcomes	6 patients free of arrhythmia for average of 35.5 months. 2 patients with recurrences underwent repeat ablation and recurrence occurred within 2 months of therapy.	Flecainide in combination with sotalolmetoprolol may be effective to control ventricular arrhythmias.	Descriptive study	Small study, no statistical assessments	
Marcus et al.	2009	19660690	Retrospective analysis of ARVC cohort	95 patients	ARVC patients with an ICD enrolled in the North American ARVC/D Registry	1) Any clinically relevant arrhythmia (sustained VT or VT/VF requiring ICD anti-tachycardia therapy of shock; 2) any ICD shock, 3) first clinically relevant arrhythmia; 4) first ICD shock	Mean follow up of 480 ± 389 days. 58 patients received a beta blocker, 38 patients on sotalol, 10 patients on amiodarone	Sotalol increased the risk of an ICD shock (HR 2.36, p=0.03) or first clinically relevant ventricular arrhythmia (HR 2.46, p=0.046), while amiodarone lowered the adjusted risk of any clinically relevant ventricular arrhythmia (HR 0.03, p=0.025). Beta blockade did not affect ventricular arrhythmnic risk.	Cox proportional hazards model	Small study, only 10 subjects received amiodarone	Exploratory analysis showed patients less likely to have a ventricular arrhythmia on atenolol compared to other beta blockers, no difference among beta blockers for other endpoints (ICD shock, first clinically relevant arrhythmia or first ICD shock)
Mazzanti et al.	2016	27931611	Cohort	301	ARVC	SCD, aborted SCD, syncopal VT or electrical storm, or cardiovascular mortality	Univariable predictors included: Male sex. HR 2.76 (1.37–5.56) p=0.005, Atrial fibrillation HR: 3.51 (1.38–8.93) p=0.008, History of syncope HR: 4.54 (2.48–8.34) p<0.001, MMVT-hemodynamically tolerated. HR 3.37 (1.87–6.07) p<0.001, Participation in strenuous exercise HR:2.90 (1.14–7.38) p=0.026, Age at presentation 21–40 yrs vs. >40 yrs HR: 2.91 (1.51–5.58) p=0.001, Proband status HR: 3.54 (1.65–7.59) p=0.001. Multivariable predictors included: Male sex. HR 2.49 (1.22–5.07) p=0.012, Atrial fibrillation HR: 4.38 (1.70–11.29) p=0.002, History of syncope HR: 3.36 (1.71–6.60) p<0.001, MMVT-hemodynamically tolerated. HR: 2.19 (1.12–4.32) p=0.023, Participation in strenuous exercise HR: 2.98 (1.12–7.90) p=0.028.	Cox regression analysis for life threatening arrhythmic events (LAE) showed that no drug (beta blocker, sotalol or amiodarone) significantly reduced the LAE events after multivariate analysis.	Cox regression analysis for effects due to drugs		Of the cohort, N=159 did not receive any antiarrhythmic drug or beta blocker

Ruwald et al.	2013	23770172	Retrospective analysis of the MADIT-CRT study population	1790 patients with heart failure	Patients who received an ICD with or without cardiac resynchronization therapy and who did not have atrial fibrillation at enrollment	Primary endpoint: occurrence of inappropriate therapy (antitachycardia pacing or shock). Secondary endpoint: inappropriate therapy for atrial arrhythmia	Carvedilol decreased risk of inappropriate therapy compared to metoprolol (hazard ratio of 0.64, p=0.002). Inappropriate therapy due to AFib also reduced more with carvedilol than metoprolol (HR of 0.5, p=0.004). Beta blockers were used in 93% of the patient population.	Carvedilol lowered inappropriate therapies by 36% compared to metoprolol, and in AFib by 50%	Cox proportional hazards model	Study of population of mixed heart failure types, unknown how many had an arrhythmogenic cardiomyopathy; retrospective and non-randomized post hoc study	Very few patients were not on a beta blocker at all, thus unclear what is the benefit of metoprolol/carvedilol compared to no beta blockade.
Wilkoff et al.	2011	20933098	Prospective RCT, MCT	464 with PM (258 MRI group; 206 no MRI as control)	9-12 weeks post PM implant	Complication during MRI or within 1 month after (complication = adverse event that resulted in an invasive intervention or the termination of significant device function) (patients underwent 14 nonclinically indicated brain and lumbar MRI sequences)	Pacing capture threshold and sensed electrogram amplitude changes were minimal and similar between study groups	No MRI-related complications occurred during 226/226 (100%) or after MRI 211/211 (100%)	One-sided 97.5% CI of 98.3%. When analyzed against the comparison rate of 90%, P <.001.	Use of MRI scanners on PM patients was specifically limited to well-defined anatomic regions.	EnRhythm SureScan Medtronic; 1.5T MRI; max SAR 2 W/kg; brain/lumbar MRI
Wlodarska et al.	2006	16760233	Retrospective cohort	126 patients with ARVC	ARVC	Assessment of thromboembolic complications	89 male, 37 female with mean age of 43.6 years. 4% had a thromboembolic complication: 2 with pulmonary embolism, 1 with RV outflow tract thrombosis, and 2 with stroke related to atrial fibrillation. Spontaneous echo contrast additionally seen in 7 patients	Annual incidence of thromboembolic complication was found to be 0.5 per 100 patients.	None	Descriptive study, low number of events	Discussion also includes references to several case reports of ARVC patients with thrombus seen in right atrium, right ventricle and/or left ventricle.

AFib = atrial fibrillation; ARVC = arrhythmogenic right ventricular cardiomyopathy; CI = confidence interval; ICD = implantable cardioverter defibrillator; HR = hazard ratio; LAE = life threatening arrhythmic events; MADIT-CRT = multicenter automatic defibrillator implantation with cardiac resynchronization therapy; MRI = magnetic resonance imaging; RCT = randomized controlled trial; RV = right ventricular; SCD = sudden cardiac death; VF = ventricular fibrillation; VT = ventricular tachycardia

Catheter Ablation											
Ablation in patients with structural heart disease											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Mallidi et al.	2011	21147263		457 participants with structural heart disease	All available randomized and nonrandomized trials of pts who underwent catheter of VT versus medical therapy - from 1965 to July 2010	Complications, VT recurrences, mortality, and study quality	Complications of catheter ablation included death (1%), stroke (1%), cardiac perforation (1%), and complete heart block (1.6%). A statistically significant 35% reduction in the number of patients with VT recurrence was noted with adjunctive catheter ablation (P = 0.001). There was no statistically significant difference in mortality.	Catheter ablation as an adjunct to medical therapy reduces VT recurrences in patients with structural heart disease but had no impact on mortality.		Unclear how many patients had ACM	
Marchlinski et al.	2016	26868693	Multicenter registry	249 patients	Only CAD patients with monomoprhic VT	CV-specific adverse events within 7 days of treatment, hospitalization duration, 6-month sustained monomorphic VT; recurrence; quality of life; long-term survival; symptomatic VT control, and amiodarone use	At 6 months, 62% of pts had no VT recurrence; the proportion of patients with implantable cardioverter-defibrillator shocks decreased from 81.2% to 26.8% (P < 0.0001); the frequency of VT in implantable cardioverter-defibrillator patients with recurrences was reduced by 50% in 63.8% of patients; and quality of life increased from 48.8% to 69.1% (P < 0.001). Amiodarone use and hospitalization decreased from 55% and 77% pre-ablation to 23.3% and 30.7%, 18.5% and 36.7%, 17.7% and 31.3% at 1, 2, and 3 years, respectively.	Ablation reduced shocks and VT episodes and improved quality of life at 6 months. 3-year nonrecurrence rate with reduced amiodarone use and hospitalizations indicate improved long-term outcomes.		Only ischemic cardiomyopathy	
Reddy et al.	2007	18160685	Randomized multicenter	128	History of MI - and sustained VT/VF; no antiarrhythmic drugs; ablation + ICD or ICD alone	The primary end point was survival free from any appropriate ICD therapy.	Mortality rate 30 days after ablation was zero, and there were no significant changes in ventricular function or functional class during the mean (+/- SD) follow-up period of 22.5+/-5.5 months. 21 pts assigned to ICD implantation alone (33%) and eight patients assigned to defibrillator implantation plus ablation (12%) received appropriate ICD therapy (antitachycardia pacing or shocks) (hazard ratio in the ablation group, 0.35; 95% confidence interval, 0.15 to 0.78, P =0.007). Among these patients, 20 in the control group (31%) and 6 in the ablation group (9%) received shocks (P = 0.003).	Prophylactic substrate-based catheter ablation reduced the incidence of ICD therapy in patients with a history of MI who received ICDs for the secondary prevention of sudden death.			
Sapp et al.	2016	27149033	Randomized multicenter	259 patients	Multicenter, randomized, controlled trial involving patients with ischemic cardiomyopathy and an ICD who had ventricular tachycardia despite the use of antiarrhythmic drugs	Primary outcome was a composite of death, VT storm, or appropriate ICD shock.	During a mean (±SD) of 27.9±17.1 months of follow-up, the primary outcome occurred in 59.1% of patients in the ablation group and 68.5% of those in the escalated-therapy group (hazard ratio in the ablation group, 0.72; 95% confidence interval, 0.53 to 0.98; P = 0.04). There was no significant between-group difference in mortality.	Patients with ischemic cardiomyopathy had a significantly lower rate of the composite primary outcome of death, ventricular tachycardia storm, or appropriate ICD shock among patients undergoing catheter ablation than among those receiving an escalation in antiarrhythmic drug therapy. No difference in mortality.		Only ischemic cardiomyopathy	

Tokuda et al.	2012	22942218	Retrospective single center	226 patients; No. of failed AAD: 2.1±1.3	Non-ischemic cardiomyopathy: dilated CMO (53%), valvular heart disease (15%); ARVC (16%); CHD (7%), cardiac sarcoidosis (6%); HCM (3%).	The primary end points: all-cause death or heart transplantation. Secondary end points: composite of death, heart transplantation, or readmission because of VT recurrence within 1 year of discharge.	ARVC had better outcomes than DCM for primary (P = 0.002) and secondary end points (P = 0.004). Sarcoidosis had worse outcome than DCM for secondary end point (P = 0.002). At 1 year after the last ablation (a mean of 1.4±0.6 procedures, 1–4), freedom from death, heart transplantation, and readmission for VT recurrence were achieved in 173 (77%) patients.	In patients with recurrent VT due to nonischemic heart disease, catheter ablation is often useful, although the outcome varies according to the nature of the underlying heart disease.			
Tung et al.	2015	26031376	Retrospective multicenter	2061 patients with structural heart disease referred for catheter ablation of scar-related VT	Scar-related VT	Freedom from VT; mortality; transplant	One-year freedom from VT recurrence was 68% in nonischemic cardiomyopathy. 10% died during follow-up. At 1 year, the estimated rate of transplant and/or mortality was 15% for nonischemic cardiomyopathy. Transplant-free survival was significantly higher in patients without VT recurrence than in those with recurrence (90% vs 71%, P < .001). In multivariable analysis, recurrence of VT after ablation showed the highest risk for transplant and/or mortality [hazard ratio 6.9 (95% CI 5.3-9.0), P < .001].	Catheter ablation of VT in patients with structural heart disease results in 70% freedom from VT recurrence, with an overall transplant and/or mortality rate of 15% at 1 year. Freedom from VT recurrence is associated with improved transplant-free survival, independent of heart failure severity.			
Tzou et al.	2017	28506710	Multicenter	740 patients	Pts with structural heart disease undergoing VT ablation at 12 centers. First time ablation was compared with repeat ablation patients.	Complications; VT recurrence; survival	Nonischemic only 53%. VT recurrence higher for repeat ablations (29% vs 24%, P = 0.001). Survival was worse for repeat ablations vs first procedures (67% vs 78%, P = 0.003)	Patients requiring repeat VT ablation differ significantly yet outcomes support this repeat ablation approach.			
Ventricular Tachycardia Ablation specifically in patients with ARVD											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Bai et al.	2011	21665983	Multicenter retrospective	49	ARVD pts undergoing either endocardial or endo-epi ablation for sustained monomorphic VT	VT recurrence or ICD therapy	3 year follow-up: freedom from VAs or ICD therapy was 52.2% for endo-only ablation and 84.6% if endo combined with epi ablation (P = 0.029), with 21.7% and 69.2% patients off antiarrhythmic drugs (P < 0.001), respectively	An endo-epicardial-based ablation strategy achieves higher long-term freedom from recurrent VAs off antiarrhythmic therapy in patients with arrhythmogenic right ventricular dysplasia/cardiomyopathy when compared with endocardial-alone ablation.			
Berruezo et al.	2017	28431051	Prospective multicenter	41	ARVD/C patients undergoing first ablation for VT	Ablation success, VT recurrence or ICD therapy	Acute success (no VT inducibility after procedure) was achieved in 90%. After 32.2 ± 21.8 months, 27% patients had VT recurrences. Left-dominant AC was associated with an increased risk of recurrence (HR = 3.41 [1.1-11.2], P= 0.044; log-rank P= 0.021).	First-line endoepicardial VT substrate ablation achieves good long-term results in AC. Left-dominant AC is associated with an increased risk of recurrence.			
Dalal et al.	2007	17662396	Single center registry	24	ARVC pts in JHMC registry	VT recurrence; survival	85% of procedures were followed by recurrence. The cumulative VT recurrence-free survival was 75%, 50%, and 25% after 1.5, 5, and 14 months, respectively.	High rate of recurrence in ARVD/C patients undergoing RFA of VT		Small sample and early ablative techniques	

Garcia et al.	2009	19620503	Single center retrospective	13	13pts with ARVC/D with failed endocardial ablations	Location of VT endocardial vs. epicardial	27 VTs were targeted on the epicardium, majority was opposite normal endocardial or ineffective endocardial ablation sites. During 18+/- 13 months, 77% had no VT, with 2 patients having only a single VT at 2 and 38 months, respectively.	Patients with ARVC/D and VT after endocardial ablation have a more extensive epicardial area of electrogram abnormalities. Epicardial ablation results in improved VT control.			
Longhi et al.	2015	25997105	Retrospective cohort	262 patients with AC	Confirmed amyloid cardiomyopathy	Prevalence, incidence, risk factors , prognostic significance of AF, effects of chronic anticoagulation	11 patients developed AF. Age, heart failure (HF), left ventricular (LV) ejection fraction, renal involvement, left atrial size and right atrial pressure were independently associated with AF. AF was associated with HF but not with increased mortality. All AF patients were prescribed warfarin and none suffered thromboembolic events.	Prevalence of AF between 15% - 40%; Age, HF, LV ejection fraction, left atrial size and right atrial pressure were the main independent risk factors.			
Philips et al.	2015	25530221	Single center cohort	30	ARVC patients who underwent endocardial/epicardial mapping and epicardial catheter ablation	VT recurrence recorded by ICD	The majority of critical VT circuits (69%) were on the epicardial surface, mostly in the subtricuspid region. 27% experienced VT recurrence after epicardial RFA, and the VT-free survival was 83%, 76%, and 70% at 6, 12, and 24, months respectively.	A significant reduction of VT burden was observed (P <.001), even among those with VT recurrence.			
Santangeli et al.	2015	26546346	Retrospective - consecutive patients	62	ARVC/D patients with VT	VT recurrence; anti-arrhythmic use	During follow-up of 56±44 months after the last ablation, VT-free survival was 71% with only a single VT episode in additional 15%. At last follow-up, 64% patients were only on β-blockers or no treatment, 21 were on class 1 or 3 antiarrhythmic drugs (11 for atrial arrhythmias), and 2 were on amiodarone as a bridge to heart transplantation.	The long-term outcome after ENDO and adjuvant EPI substrate ablation of VT in arrhythmogenic right ventricular cardiomyopathy is good. Most patients have complete VT control without amiodarone therapy and limited need for antiarrhythmic drugs.			
Ventricular arrhythmia ablation in other VT syndromes											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Kumar et al.	2016	27506821	Retrospective multi center	25	LMNA mutation patients with drug-refractory ventricular tachycardia	VT recurrence, complications, death/transplant/mechanical circulatory support	After multiple procedures acute success (noninducibility of any VT) was achieved in only 25% of patients. Partial success and failure was attributed to intramural septal substrate in 13 of 18 patients (72%). Complications occurred in 25% of patients. After a median follow-up of 7 months after the last procedure, 91% experienced ≥1 VT recurrence, 44% received or were awaiting mechanical circulatory support or transplant for end-stage heart failure, and 26% died.	Catheter ablation of VT associated with LMNA cardiomyopathy is associated with poor outcomes including high rate of arrhythmia recurrence, progression to end-stage heart failure, and high mortality. Basal septal scar and intramural VT origin makes VT ablation challenging in this population.		Small cohort	Ablation seems to be of palliative benefit

AAD = antiarrhythmic drug; AC = amyloidotic cardiomyopathy; ACM = arrhythmogenic cardiomyopathy; AF = atrial fibrillation; ARVC = arrhythmogenic right ventricular cardiomyopathy; ARVD = arrhythmogenic right ventricular dysplasia; CAD = coronary artery disease; CHD = congenital

Exercise Restriction

Study name or author	Year	PubMed ID (PMID)	Study type	Study size	Inclusion criteria	Endpoints	Findings	Outcome results	Statistical values	Limitations	Comments
Corrado et al.	1997	9362410	Retrospective regional area: autopsy cohort	42 ARVC	Inclusion: Pathologic dx of ARVC at autopsy or heart transplant Mean age 29.6±18 y		SCD exercise related in 47%				
Corrado et al.	2003	14662259	21-year prospective cohort study including all young people in Veneto region (1979-1999)	300 SCD (55 in athletes, 245 in non-athletes) from among >1 million	Arrhythmogenic right ventricular cardiomyopathy (ARVC) was diagnosed in the presence of gross and/or histologic evidence of regional or diffuse transmural fibrofatty replacement of the right ventricular free wall and in the absence of other known cardiac or non-cardiac causes of death .	SCD - unexpected death as a result of natural causes in which a loss of all functions occurred instantaneously or within 1 h of the onset of collapse symptoms.	Young athletes had a 5-fold higher risk of dying of ARVD/C compared with nonathletes	The RR of SD among athletes versus non-athletes was 1.95 (CI 1.3 to 2.6; p = 0.0001) for males and 2.00 (CI 0.6 to 4.9; p = 0.15) for females. The higher risk of SD in athletes was strongly related to underlying cardiovascular diseases suc h as arrhythmogenic right ventricular cardiomyopathy (RR 5.4, CI 2.5 to 11.2; p < 0.0001)			Exercise collection methodology: Preparticipation screening by history, physical examination, 12-lead electrocardiogram, and limited exercise testing, as required by Italian law. Exercise/athlete definitions: Young competitive athletes were defined as adolescents and young adults (age 12 to 35 years) who participated in an organized sports program requiring regular training and competition.
Corrado et al.	2006	17018804	Autopsy cohort from Veneto region of Italy (1979-2004)		Adolescents and young adults as above	Comparison of SCD rates and causes after implementation of a pre-participation screening program for young athletes	Implementation of a pre-participation screening program in Italy resulted in a sharp decline in ARVC/C-associated sudden deaths.				Exercise collection methodology: as above Exercise/athlete definitions: as above
Gupta et al.	2017	28506445	Retrospective registry-based autopsy cohort	66 ARVD/C cases in whom disease was first recognized following SCD (N=45) or SCA (N=21); 352 cases meeting TFC diagnosed alive	ARVD/C cases in whom disease was first recognized following SCD (N=45) or SCA (N=21) compared to 352 TFC+ cases diagnosed before any arrest	Age at arrest/1st VT; survival from first symptom to SCD/SCA/VT. Association of genotype with arrest	Physical exertion precipitated most arrests (N=46, 72%). Among the cases in whom exertion precipitated arrest, most (32/46, 70%) were participating in athletic activities that had a high dynamic demand.	Cases whose arrest occurred with exertion were disproportionately carriers of an ARVD/C-associated desmosomal mutation (87% exertional SCD/SCA occurred in mutation carriers vs. 50% non-exertional arrests; p=0.01). The SCD/SCA cohort was disproportionately male (65% SCD/SCA vs. 50% living, p=0.03) and younger at both first reported symptom (27.7 +/- 13.5 years SCD/SCA vs. 33.0 +/- 13.6 years living, p=0.01) and first sustained ventricular arrhythmia (VA) (29.3 +/- 13.8 years SCD/SCA vs. 35.6 +/- 12.9 years living, p<0.001).		Pathology samples not reviewed, only overread of autopsies by cardiac pathologists.	Exercise collection methodology:Review of circumstances of death on autopsy/in medical record. Exercise/athlete definitions: Circumstances of arrest were grouped into three categories: physical exertion, daily activity or during sleep/in bed. Activities involving physical exertion were classified as requiring low (<40% max O2), moderate (40-70% max O2) or high (>70% max O2) cardiovascular demand.

James et al.	2013	23871885	Single center, observational cohort study.	87	Inclusion 1. Carriers of a single pathogenic desmosomal variant (both affected and at-risk family members); 2. Could speak English. Exclusion 1. Patients and family members with multiple pathogenic variants; 2. Patients without mutations	1) Penetrance (diagnosis per 2010 TFC); 2) Lifetime survival free from first sustained VT / SCD / SCA; 3) Lifetime survival free from Class C heart failure, 4) Sustained ventricular arrhythmia in follow-up among mutations carriers who did not present clinically with sustained VT	Participation in endurance exercise (Class C) is associated with poorer lifetime survival free from sustained ventricular arrhythmias. Those participating in top quartile average annual duration had poorer survival free from sustained VT/VF. Among variant carriers who did not present with VT/VF those who did top quartile duration exercise prior to presentation and reduced exercise were less likely to develop a first VT than those who continued to do top quartile exercise.	Participation in endurance exercise is associated with increased penetrance and worse lifetime survival free from sustained ventricular arrhythmias and class C heart failure. Overall, 31 endurance athletes (55%) had experienced at least 1 sustained VT/VF at last follow-up compared with 8 (26%) nonathletes (p = 0.008)	1) Endurance athletes had a lower lifetime survival free from VT/VF (p=0.013). (2) Among 61 individuals who did not present with VT/VF, the 13 subjects experiencing a first VT/VF event over a mean follow-up of 8.4 years were all endurance athletes (p = 0.002). 3) Survival from a first VT/VF event was lowest among those who exercised most (top quartile) both before (p = 0.036) and after (p = 0.005) clinical presentation. Among individuals in the top quartile, a reduction in exercise decreased VT/VF risk (p = 0.04).	Recall and ascertainment bias in interviews, missing ARVC cases presenting with sudden cardiac death	Exercise collection methodology: Interviewed about lifetime exercise type, duration, and intensity from age 10 Exercise/athlete definitions: 1. Endurance athlete: Participant in a sport with a high dynamic demand (>70% maximum O2), as defined by the 36th Bethesda Conference Classification of Sports (Task Force 8), done for at least 50 h/year at vigorous intensity from age 10 to last clinical follow-up. Vigorous intensity is "a very hard activity that requires close to all-out effort." Vigorous activity causes large increases in breathing or heart rate and is done for at least 10 minutes continuously unless the sport precludes this duration (e.g. football, sprinting). 2. Average hours/year of all regular exercise; 3) Change in exercise duration after clinical presentation (quartiles of hours per year)
La Gerche et al.	2010	20525856	Observational cohort study of athletes with complex VA	47 athletes with complex VA of RV morphology	Inclusion: Exclusion: idiopath/ic RVOT tachycardia	1. Diagnosis of ARVC (definite or suspected) ; 2) Prevalance of desmosomal pathogenic variant; 3) Family history suggestive of ARVC	Athletes with definite or probable ARVC had an unexpectedly low frequency of desmosomal pathogenic variants.	Among 41 athletes with definite or probable ARVD/C, only six had a definite or possible desmosomal mutation and few had a family history of disease. Mutation carriers had done significantly less exercise than the remaining cases.			Exercise/athlete definitions: Athlete: intensity ≥6 METS, duration ≥4 h/wk
Lie et al.	2018	29929667	Observational	173	Definite ARVC	Sustained ventricular arrhythmia in follow-up; right and left ventricular size and function		High intensity exercise an independent predictor of ventricular arrhythmias even after adjusting for long exercise duration. Exercise dose (high and long) was the best predictor of structural dysfunction.		Exercise in follow-up not evaluated	Exercise collection methodology: Interview at diagnosis Exercise/athlete definitions: Median duration per week, “high intensity” = >6 METS
Mazzanti et al.	2016	27931611	Observational cohort from single center (Italy)	301 ARVC patients	2010 TFC	Life-threatening arrhythmic event: SCD, aborted cardiac arrest, syncopal VT or electrical storm, or cardiovascular mortality	Participation in strenuous exercise after diagnosis is associated with worse survival from first LAE	Participation in strenuous exercise after the diagnosis associated with poorer survival from life-threatening arrhythmic event(HR: 2.98; p = 0.028)			Exercise collection methodology: Athletes participating in "strenuous exercise" further interviewed to assess METS. Others did not provide detailed exercise history. Exercise/athlete definitions: "Strenuous exercise": Regular (≥5 hours/week for ≥1 year) participation in

Ruwald et al.	2015	25896080	North America ARVC registry (observational cohort study), 18 centers	108 probands. Pre-ARVD they were: competitive (n = 41), recreational (n = 48), and inactive (n = 19)	Inclusion: Probands enrolled in NA ARVC Registry affected or borderline per the 2010 TFC. Registry exclusion: 1. ICD > 2 years before enrollment; 2. Diagnosis > 2 years before enrollment. 3. < age 12. Substudy exclusion: 1) Unknown exercise level before diagnosis	Combined VTA/death. VTA= center-reported documented clinical sustained VT episodes with a duration of more than 30s, or appropriate ICD therapy for VT occurring both before and after enrollment in the registry	Patients in competitive sports were diagnosed at a younger age and had worse survival free from death/VT in follow-up. Those who did competitive exercise pre-diagnosis who reduced to recreational or sedentary after diagnosis had better survival free from the endpoint than those who continued competitive exercise. No difference in RVEF or LVEF among the groups at baseline. However competitive athletes on CMR had worse RVEDV/BSA (0.007) and LVEDV/BSA (0.004).	Competitive sport was associated with a significantly higher risk of VTA/death when compared with both recreational sport [HR = 1.99 (1.21-3.28), P = 0.007] and inactive patients [HR = 2.05 (1.07-3.91), P = 0.030]. No increased risk of VTA/death was associated with recreational sport when compared with patients who were inactive [HR = 1.03 (0.54-1.97), P = 0.930]. Symptoms developed at an earlier age in patients who participated in competitive sport (30 ± 12 years), when compared with patients who participated in recreational sport (38 ± 17 years) (P = 0.015) and inactive patients (41 ± 11 years) (P = 0.002). No difference in age at first symptom was seen between patients who participated in recreational		Limited refinement in exercise history measurement	The survival curve for "recreational" athletes falls in between that of competitive and inactive patients. Lack of statistical significance in difference may be a power issue. Exercise collection methodology: Patient questionnaire at registry enrollment. Exercise/athlete definitions:Self defined as inactive or participant in recreational or competitive athletics before and after diagnosis at study enrollment. Patients were further asked what type of sport they most often practiced, and at what age they first initiated the sport. A group of sports were assigned as high dynamic demand: basketball, soccer, hockey, skiing, running, biking, and tennis, and a variable of low to moderately dynamic sport defined as bowling, golf, weight lifting, wrestling, baseball, or softball from Pelliccia et al 2005 EHJ guidelines.
Saberniak et al.	2014	25319773	Observational cohort from single center	110 (65 affected regardless of genotype plus 45 at-risk desmosomal variant carriers)	Inclusion: ARVC probands and mutation positive family members. Genotyping in 100 patients - 75% mutation positive, PKP2 91%.	Structural dysfunction, exercise-induced VA	Exercise induced VA in 37% of patients, more likely in athletes p<0.001 and in those with exercise duration ≥2.5 h/wk x 6 y	Athletes among the asymptomatic mutation carriers had lower V function and more RV abnormalities. Athletes had a higher frequency and earlier onset of VA. Only athletes required transplant.	RV function was reduced in athletes compared with non-athletes (FAC 34 ± 9% vs. 40 ± 11%, RVGLS -18.3 ± 6.1% vs. -22.0 ± 4.8%, RVEF 32 ± 8% vs. 43 ± 10%, all P < 0.01). LV function by LVEF and LVGLS was reduced in athletes compared with non-athletes (LVEF by echocardiography 50 ± 10% vs. 57 ± 5%, LVEF by MRI 46 ± 6% vs. 53 ± 8%, and LVGLS -16.7 ± 4.2% vs. -19.4 ± 2.9%, all P < 0.01). The METs × minutes/week correlated with reduced RV and LV function by echocardiography and MRI (all P < 0.01). The LVEF by MRI was also reduced in subgroups of athlete index patients		Exercise collection methodology: Telephone interview Exercise/athlete definitions: Athlete: intensity ≥6 METS, duration ≥4 h/wk during a minimum of 6 years

Sawant et al.	2014	25516436	Single center, observational cohort study	Total: 82 Desmosomal mutations: 39 Gene-elusive: 43	Inclusion: ARVC patients 1) meeting 2010 TFC, 2) who had undergone sequencing for at least the desmosomal genes, and 3) were index cases. Exclusion: Patients ascertained as family members	1. Age at presentation; 2 Meet structural TFC; 3. survival free from ventricular arrhythmia		Gene-elusive non-familial ARVC is associated with very high intensity exercise. All gene elusive patients met the definition of a Class C athlete.	Gene-elusive patients who had done the most intense (top quartile MET-Hrs/year) exercise prior to presentation had a younger age of presentation (P=0.025), greater likelihood of meeting ARVD/C structural Task Force Criteria (100% versus 43%, P=0.02), and shorter survival free from a ventricular arrhythmia in follow-up (P=0.002).		Exercise collection methodology: Interviewed about lifetime exercise type, duration, and intensity from age 10 Exercise/athlete definitions: 1. Endurance athlete (as above); 2. Average hours/year of exercise; 3. MET-Hours per year of exercise (intensity)
Sawant et al.	2016	26321091	Pedigree analysis - drawn from single center observational cohort	10 families (37 variant carriers)	Inclusion: 1. Carriers of a single pathogenic PKP2 variant (both affected and at-risk family members)	1. Diagnosis by 2010 TFC; 2. First sustained VT/VF	After adjusting for age, sex, & family membership; participation in endurance athletics, (OR: 7.4, p=0.03), higher intensity exercise (OR: 4.2, p=0.004) were associated with dx of ARVCD. Family members restricting exercise to ≤650 MET-Hr/yr (AHA upper limits) were significantly less likely to have ARVC dx (OR: 0.07, p=0.002); no VT/VF.	Participation in AHA-minimum recommended exercise for healthy adults may be a reasonable recommendation for PKP2 variant carriers who are relatives of ARVD patients.	Participation in endurance athletics, (OR: 7.4, p=0.03), higher intensity exercise (OR: 4.2, p=0.004) were associated with dx.; Family members restricting exercise to ≤650 MET-Hr/yr (AHA upper limits) were significantly less likely to have ARVC dx (OR: 0.07, p=0.002)	Small sample size; PKP2 variants only	Exercise collection methodology: Interviewed about lifetime exercise type, duration, and intensity from age 10 Exercise/athlete definitions: 1. Endurance athlete as above; 2. Average hours/year of exercise; 3. MET-Hours per year of exercise (intensity); 4. Exercise relative to AHA target guideline for healthy adults (450-750 METmin
Sen-Chowdhry et al.	2007	17372169	Observational cohort (Britain)	116 patients	1994 TFC - meeting definite or modified criteria	Right and left ventricular size and function. VT, NSVT		Compared with other subjects, athletes had increased RVEDV (mean, 174±30% versus 122±25%;*P* <0.0001), lower RVEF (mean, 44±7% versus 53±7%; *P* =0.0001), increased LVEDV (mean, 134±27% versus 110±18%; *P* <0.0001), and higher RV lesion scores (*P* =0.0004). No significant differences existed in LV lesion scores, the prevalence of notable ventricular arrhythmia, or nonsustained VT.		1994 TFC. Only very high level athletes captured	Exercise collection methodology: Part of clinical history Exercise/athlete definitions: 11 endurance athletes, long-term endurance training (equivalent to >1 marathon a year for >10 years). Detailed characterization "outside the scope of the clinical workup"

Te Riele et al.	2015	29759408	Observational cohort multicenter (exercise data single center)		For exercise subanalysis: Carrier of a desmosomal variant who had participated in an exercise interview			Among desmosomal variant carriers, cases presenting prior to adulthood were more likely to have been an endurance athlete in adolescence than ARVC cases presenting as adults. There was a trend associated with greater duration (hours/year) of exercise in adolescent exercise among cases presenting as adolescents.			Exercise collection methodology: Interviewed about lifetime exercise type, duration, and intensity from age 10
Wang et al.	2018	29909402	Observational	129	Definite ARVC with ICD	First appropriate therapy for sustained ventricular arrhythmias		Greater reduction in exercise dose conferred greater reduction in risk of ventricular arrhythmias. Patients without desmosomal mutations and those with primary-prevention ICDs benefited more from exercise reduction.		Programming at discretion of local care provider	Exercise collection methodology: Exercise intervies. Exercise/athlete definitions: Change in exercise (average MET-Hrs/year) from 3 years before presentation to afterwards

AHA = American Heart Association; ARVC = arrhythmogenic right ventricular cardiomyopathy; ARVD = arrhythmogenic right ventricular dysplasia; CI = confidence interval; CMR = cardiac magnetic resonance imaging; dx = diagnosis; EHJ = European Heart Journal; FAC = fractional area change;

ACM Amyloidosis											
Treatment of Amyloidosis											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Bradyarrhythmias											
Eriksson and Olofsson	1984	6205372	Retrospective cohort	20	20 pts with familial amyloidosis (1968 - 1983)	Symptoms; complications; survival	Complete heart block (11), second degree heart block (1), sinus nodedysfunction (5), and atrial fibrillation with a slow ventricular rate (3)	All patients improved symptomatically; high lead dislodgement (4); no life expectancy related to disease progression			
Reisinger et al.	1997	9316537	Non-randomized prospective	25	Twenty-five patients with biopsy-proven AL	Electrophysiologic abnormalities in AL (primary) amyloidosis with cardiac involvement	Sinus and AV node function was preserved. Infra-His (HV) conduction times abnormal. mean HV: 79 +/- 18 ms (range 50 to 110)	43% of patients died suddenly. HV prolongation was sole independent predictor of sudden death by multivariate analysis (p = 0.05)			
Sayed et al.	2015	25549725	Non-randomized prospective	20	20 consecutive patients with newly diagnosed severe cardiac AL amyloidosis and symptoms of syncope or pre-syncope	Death or malignant brady/tachycardia arrhythmia	13pts died; median survival 61 days from device insertion. In all evaluable deaths: death was heralded by bradycardia, usually complete atrioventricular block (CAVB), followed shortly thereafter by pulseless electrical activity.	Bradyarrhythmias heralded terminal cardiac decompensation in most patients with severe cardiac AL amyloidosis.			Supports a study of prophylactic pacemaker insertion in this patient population.
Atrial arrhythmia											
Barbhaiya et al.	2016	26400855	Retrospective cohort	18 pts with atrial arrhythmias taken for ablation	Confirmed CA and arrhythmia undergoing EPS	Define intracardiac conduction, atrial arrhythmia substrate, and ablation outcomes in a group of advanced CA, and compared to age- and gender-matched patients without CA.	Prolonged AV (HV) conduction in all pts; more extensive LA low-voltage areas and more ATs vs normal hearts. The recurrence rate for AT/AF ablation at 1 year was 83% vs 25%.	Extensive conduction system disease and LA endocardial voltage abnormality; catheter ablation for persistent AT/AF high recurrence rate		Small cohort; no AV node ablation group; all persistent AF	
Longhi et al.	2015	25997105	Retrospective cohort	262 patients with AC	Confirmed amyloid cardiomyopathy	Prevalence, incidence, risk factors, prognostic significance of AF, effects of chronic anticoagulation	11 patients developed AF. Age, heart failure (HF), left ventricular (LV) ejection fraction, renal involvement, left atrial size and right atrial pressure were independently associated with AF. AF was associated with HF but not with increased mortality. All AF patients were prescribed warfarin and none suffered thromboembolic events.	Prevalence of AF between 15% - 40%; Age, HF, LV ejection fraction, left atrial size and right atrial pressure were the main independent risk factors.			
Tan et al.	2016	27422772	Retrospective cohort	26 pts with atrial arrhythmias taken for ablation	Confirmed CA and arrhythmia undergoing atrial ablation	One-year and 3-year recurrence-free survival; symptom improvement; AV node ablation	One-year and 3-year recurrence-free survival were 75% and 60%, respectively. NYHA symptom improvement 6 months postablation was observed in both CA-A and CA-AVN groups: 7/10 (70%) and 4/8 (50%).	Catheter ablation provides important symptomatic benefit. Mortality from the underlying disease remains a significant issue for AL amyloid.		Small cohort; no comparator	
Ventricular arrhythmia											
Dubrey et al.	1998	9578896	Retrospective single center cohort	232	Primary (AL) cardiac amyloidosis	Clinical presentation, investigations, therapy, prognosis and outcome of 232 patients with primary (AL) cardiac amyloidosis	AL cardiac amyloidosis was unusual in isolation (3.9%), and most frequently patients had features of multiorgan dysfunction; heavy proteinuria and features of malabsorption predominating.	Heart involvement represents the worst prognostic indicator, with a median survival from diagnosis of 1.08 years, falling to 0.75 years with the onset of heart failure.		Advances in therapy for AL amyloid is associated with improved clinical outcomes.	

Hamon et al.	2016	27513652	Multicenter retrospective	45	CA with ICD implantation	Appropriate ICD therapy and survival	Follow-up of 17±14months, 12 patients (27%) had at least 1 appropriate ICD therapy occurring after 4.7±6.6months; 12 patients died (27%) and 6 underwent cardiac transplantation (13%)	Appropriate ICD therapies are common (27%) in CA patients.		Small cohort; mixed pathology	
Kristen et al.	2008	18242546	Retrospective single center cohort	19	19 patients with CA with ICDs; hx of syncope and/or PVCs	Death or appropriate ICD therapy	Follow-up: 811 +/- 151 days, 2pts received appropriate therapies; 2pts cardiac explant; 6 died of EMD; bradycardias requiring ventricular pacing for rates<40/min <1%	Most common cause of death was electromechanical dissociation		Small series	
Lin et al.	2013	23489983	Retrospective single center cohort	53	CA with ICD implantation; 77% 1° prevention; 23% 2° prevention	Appropriate ICD therapies; mortality	Appropriate ICD therapy: 32% in the first year	A high rate of appropriate ICD shocks was observed especially in patients with AL-type amyloidosis. However, appropriate ICD therapy did not translate into overall survival benefit.		Small cohort; mixed pathology	
Mlcochova et al.	2006	16643368	Case series	2	2 patients with CA and repetitive VF	N/A	The electrical storms were drug resistant. Ablation of culprit PVCs prevented further VF.	PVC's recognized to trigger VF in this small series		Small series	
Rezk et al.	2018	28485005	Meta-analysis of 4 major studies	82	CA - AL subtype only	Contrast ICD therapies in their UK cohort of 15 patients with AL CA - with other published cohorts	27% received appropriate therapies. 75% survived post-ICD therapy; overall cohort survival (87%). Compared with overall worldwide cohort: 28% received ICD appropriate ICD therapies; overall survival 49%	ICD implantation, in selected patients with AL amylodiosis, delivers appropriate therapy and is life saving in the short term, but long-term survival benefit remains unclear.			AL only
Varr et al.	2014	24121001	Single center	31 patients	CA with ICD, PM or ambulatory monitoring	NSVT, VT, ICD therapy	NSVT was common and occurred in 74%; sustained VT/VF occurred in 19%; ICD therapy was successful in 80%; in pts who received successful ICD therapy, subsequent survival: 6 weeks - 19 months (2 alive at submission)	80% of the patients with cardiac amyloidosis had successful ICD therapy for life threatening ventricular arrhythmias.			More salutary effect of ICD's on arrhythmia termination and survival
Therapy											
Gertz et al.	1985	4003314	Case series	2 patients	Deleterious effects noted with Ca blockers		Both patients sustained significant symptomatic decline with the use of verapamil and nidefipine	Improvement of symptoms after discontinuation of medications		n=2	
Gertz et al.	1985	4003315	In-vitro	1 patient	Amyloid fibrils isolated from the spleen of a single patient		In all experiments, nifedipine was bound to isolated amyloid fibrils in vitro.	Similar binding noted with digoxin			The binding of nifedipine to amyloid should be considered as one possible mechanism for the enhanced negative inotropic effect that can be seen in patients with amyloid heart disease who are given calcium channel-blocking agents.
Griffiths et al.	1982	6891504	Case report	1 patient	Deleterious effects noted with nifedipine		Echo before and after 10mg sublingual nifedipine	Acute severe LV failure		n=1	
Muchtar et al.	2018	29529877	Retrospective single center cohort	107 patients	AL amyloidosis and digoxin use		Digoxin dose was reduced in 16% (high serum drug concentration or worsening renal function). Significant arrhythmias developed in 11%.	Arrhythmias presented as terminal events in five patients; four with bradycardia followed by pulseless electrical activity (PEA) with ventricular tachycardia/fibrillation (VT/VF) during resuscitation			Digoxin may be cautiously utilized in AL amyloidosis patients.
Pollak and Falk	1993	8339658	Case report	1 patient	Deleterious effects noted with Ca blockers		Symptomatic decline with verapamil	Withdrawal of therpay resulted in improvement		n=1	

Rubinow et al.	1981	7014028	In-vitro				Basic digoxin binding assay from: purified primary and secondary amyloid fibrils, a normal human liver and heart homogenate and a homogenate from the heart of a patient with amyloid cardiomyopathy	Isolated amyloid fibrils bind digoxin			Suggests that this interaction may play some role in the sensitivity to digitalis that has been observed in some patients with amyloid cardiomyopathy

AC = amyloidotic cardiomyopathy; AF = atrial fibrillation; AL = light-chain amyloidosis; AT = atrial tachycardia; AV = atrioventricular; CA = cardiac amyloidosis; CA-A = atrial arrhythmia ablation; CA-AVN = AV nodal ablation; CAVB = complete atrioventricular block; EMD = Electromechanical

Left Ventricular Noncompaction											
Study name or author	**Year**	**PubMed ID (PMID)**	**Study type**	**Study size**	**Inclusion criteria**	**Endpoints**	**Findings**	**Outcome results**	**Statistical values**	**Limitations**	**Comments**
Andreini et al.	2016	27855806	Prospective assessment of a cohort	N=113 patients	Patients with echo diagnosis of LVNC and underwent CMR (cardiac MRI)	Composite of cardiac events of thromboembolic events, heart failure hospitalizations, ventricular arrhythmia and cardiac death	CMR criterion of noncompacted/compacted ratio>2.3 in end diastole confirmed in all patients. At mean follow up of 48 +/- 24 months, cardiac events seen in 36 patients. LV dilation, reduced LV ejection fraction and LV noncompacted myocardial mass of >20% was more frequent in patients that had cardiac events. LV fibrosis seen in 11 patients. CMR predictors of cardiac events were LV dilation and late gadolineum enhancement (LGE), and LGE associated with improved prediction of events.	With CMR, degree of LV trabeculation is not prognostic for cardiac events. LV dilation, LV systolic dysfunction and LGE were predictive.	Chi-square or student t test or ANOVA or Kurska-Wallis tests. Outcome predictions assessed by Cox regression and with multivariate analyses. Kaplan-Meier survival anaysis performed for event free survival.	Number of events was low. No genetic characterizaton of study patients	
Brescia et al.	2013	23633270	Retrospective review	242 subjects	All patients diagnosed with LVNC between 1/1990-1/2009	Primary endpoint: Time to cardiovascular death or transplant	31/242 (12.8%) died, 13/242 (5.4%) transplanted 150/242 (62%) presented with or developed cardiac dysfunction. Presence of cardiac dysfunction was strongly associated with mortality (hazard ratio, 11; P<0.001). ECG abnormalities were present in 87%, with ventricular hypertrophy and repolarization abnormalities occurring most commonly. Repolarization abnormalities were associated with increased mortality (hazard ratio, 2.1; P=0.02). 80/242 (33.1%) had an arrhythmia, and those with arrhythmias had increased mortality (hazard ratio, 2.8; P=0.002). 42/242 (17.4%) had VT, with 5 presenting with resuscitated SCD. 15/242 sudden cardiac deaths (6.2%). Nearly all patients with sudden death (14 of 15) had abnormal cardiac dimensions or cardiac dysfunction.	80/242 (33.1%) had an arrhythmia, and those with arrhythmias had increased mortality (hazard ratio, 2.8; P=0.002). 15/242 sudden cardiac deaths (6.2%). Nearly all patients with sudden death (14 of 15) had abnormal cardiac dimensions or cardiac dysfunction.	Presentation within the first year of life was associated with increased mortality (hazard ratio [HR], 2.1; 95% confidence interval [CI], 1.0–3.9; P=0.02). The hazard of sudden death increased significantly in patients with a preceding arrhythmia (HR, 7.6; 95% CI, 1.5–37.8; P=0.01). The presence of cardiac systolic dysfunction was significantly associated with death or transplantation (HR, 11; 95% CI, 2.6–45; P<0.001).	Retrospective study	
Caliskan et al.	2011	21332865	Prospective assessment of a cohort	N=77 patients	LVNC patients	Identify the indications for ICD implantation and outcomes in noncompaction cardiomyopathy patients	ICD in 57% of patients with 12 for secondary prevention (VF, sustained VT) and 32 patients with a primary prevention indication for heart failure. Over mean follow up of 33 months and within a median time of 6.1 months, 8 patients (4 with a primary prevention ICD) had appropriate therapies for sustained VT. 9 patients had inappropriate therapies with 6 in the primary prevention group.	Appropriate ICD therapies are seen in both primary and secondary prevention patient groups with noncompaction. Secondary prevention factors included as well 7 with cardiac arrest/VF, 5 with sustained VT and 2 with syncope	Kaplan-Meieir survival analysis with Cox regression analyses	Small number of patients with therapies overall	

Gati et al.	2014	25006201	Prospective assessment of a cohort	N=102 patients	Pregnant, followed in first and third trimesters and then post partum	Determination of patients that met echo criteria for LVNC over time during pregnancy and postpartum	26 women (25.4%) developed increased trabeculations, 8 meeting LVNC criteria. During postpartum period (follow up of 24 +/- 3 months) 19 women (73)% resolved trabeculations and 5 with marked reduction. Women also expressed in pregnancy increased heart rate, stroke volume, cardiac output, LV volume and mass.	Pregnancy induced LV trabeculations in a significant proportion of women that resolve or reduce in the postpartum period. This suggests that trabeculations occur from increased LV loading conditions, and thus could occur in other situations of increased load, such as heart failure or familial cardiomyopathy.	Chi-square or Fisher exact test to assess differences in group proportions, repeated measures ANOVA to evaluate changes over time, logistic regression to assess factors to predict presence of increased trabeculations	Echo utilized, but not MRI as there were concerns for safety of performance of an MRI in the first trimester	Other factors that were not studied, such as estrogen concentration, related to pregnancy but not related to LV loading may have accounted for trabeculations.
Gleva et al.	2017	28917495	Retrospective review	661 subjects	All patients 18 years or older in the NCDR Registry diagnosed with LVNC and having an ICD implanted	Primary endpoint: Occurrence of in-hospital adverse events	Single-chamber ICDs predominated in the LVNC patient group. Lead extraction was infrequent in LVNC. Patients with LVNC had a moderate reduction in LV systolic function, were more likely to have a primary prevention indication for ICD placement, and had predominantly single-chamber devices implanted.	In-hospital complication rates for LVNC patients was less than 2%. Patients with LVNC had a moderate reduction in LV systolic function.	Standard descriptive statistics included mean (standard deviation) for continuous variables and frequency (# and %) for categorical variables. Univariate associations were examined using the chi-squared test for categorical variables and the F-test in analyses of variance for continuous variables. P values of <0.05 were considered statistically significant.	Registry-related limitations in data collected and time-frame covered, as well as lack of clarity regarding method of diagnosis of LVNC and prior clinical presentation(s).	
Hoedemaekers et al.	2010	20530761	Retrospective cohort	58 patients and 194 relatives	Patients with isolated LVNC and first and second degree relatives	Studies consisted of cardiological family studies with genetic testing	Familial cardiomyopathy in 64% with LVNC, hypertrophic cardiomyopathy and dilated cardiomyopathy. Of 17 asymptomatic relatives, 9 had noncompaction, and 8 carriers had nonpenetrance, thus 44% of familial disease was undetected by family history alone. Mutations seen in 11 genes in 41% of probands.	LVNC has variable presentation and genetic counseling needed along with DNA diagnostics and cardiological family screening.			

Ivanov et al.	2017	28899950	Prospective assessment of a cohort	N=700 patients	Patients referred for cardiac MRI	Primary outcome - combined endpoint of time to death, ischemic stroke, ventricular tachycardia/ventricular fibrillation (VT/VF), heart failure hospitalization. Secondary outcomes were: all-cause mortality and time to first of following: cardiac death, ischemic stroke, VT/VF or heart failure hospitalization	Four imaging criteria were assessed related to ratio of noncompacted to compacted myocardium in end diastole or end systole or mass ratio between total and trabeculae mass or fractal dimension. Prevalence of LVNCE varied from 3-39% depending on imaging criteria used, but those that met Captur criteria (3%) also had met diagnosis by the other 3 criteria.	Median follow up of 7 years. There were 253 events in 209 patients with 134 deaths, 91 hospitalization for heart failure, 16 patients with stroke, 12 patients with malignant ventricular arrhythmias and 39 patients had multiple events. There were no differences in primary or secondary outcomes between those patients with or without LVNC regardless of the criteria used for diagnosis of LVNC.	Mann-Whitney for continuous variables, chi-square for categorical. First adverse event counted for primary and secondary outcomes. Clinical outcomes analyzed with multivariable cox proportional hazard model with forward and backward selection and controlled for age, sex, bodymass index, presence of diabetes, LV and right ventricular ejection fraction, presence of LGE, indication for CMR. Receiver-operating characteristic analysis to assess prognostic performance of parameters and define presence of LVNC.		
Kohli et al.	2008	17993472	Retrospective cohort	N=199 patients	Patients with LV systolic impairment	Determination of patients that met echo criteria for LVNC	47 of 199 patients with LV systolic impairment met one or more echo definitions for LVNC. These patients were younger (p=0.002), had larger LV dimension in end-diastole (P<0.001) and a smaller left atrium (p=0.01) compared to a group of 60 normal controls. Black individuals more likely to fulfill LVNC criteria, including among controls.	High percentage of patients with heart failure fulfill current echo criteria for LVNC, suggesting current criteria are too sensitive, especially in black individuals.	Student t tests for continuous variables, and chi-square for categorical variables. For multiple comparisons used Bonferroni corrections with P then set to <=0.0025.	Echo data was collected but without specific focus for LVNC but controls were studied prospectively to look for LVNC. Control group not age-matched.	
Miller et al.	2017	29212898	Retrospective cohort	128 pediatric patients with LVNC	Pediatric patients with LVNC	Presence or absence of a positive cardiomypathy gene panel test result	65 patients had a cardiomyopathy gene panel and 10 had known variant testing. Yield was 9% for cardiomyopathy gene panel testing. LVNC severity on imaging not related to genetic testing, cardiac features, etiology, family history or myocardial dysfunction. Those with isolated LVNC were less likely to have a positive genetic test result.	Cardiomyopathy gene panel testing was helpful for individuals with a cardiomypathy with LVNC, but was not helpful for those with isolated LVNC and no family history of a cardiomyopathy.			
Muser et al.	2017	27890738	Retrospective review	9 subjects	All patients diagnosed with LVNC between 1/2006-12/2014 undergoing EP study and catheter ablation	Primary endpoint: Survival free of any VA after single or multiple ablations. Secondary endpoint: Survival free of death or transplantation	8/9 patients (89%) had LV dysfunction. Patients presenting with VT had abnormal electroanatomic substrate in mid- to apical LV segments, matching the noncompacted myocardial segments identified by CMR/echo. Over followup, VAs recurred in 1/9 (11%), significant improvement in LV function in 4/8 (50%)	After median follow-up of 4 years (range 1-11) and mean of 1.8 ± 1.1 procedures, VAs recurred in 1 patient (11%), significant improvement in LV function occurred in 4/8 (50%); no deaths or transplants	Median baseline LVEF 40% (25th-75th centile 30%-50%) vs. median LVEF at last follow-up 50% (25th-75th centile 35%-55%), P=0.048	Small, selected patient population enrolled (LVNC with sustained VT or symptomatic PVCs refractory to medication). Selection bias (patients referred for catheter ablation)	

Sidhu et al.	2014	23689383	Retrospective cohort	Total of 59 cardiomyopathy patients and 20 controls	Patients with cardiomyopathy: LVNC (n=8), non-ischemic dilated cardiomyopathy (n=11), hypertrophic cardiomyopathy (n=11), severe aortic stenosis(n=10), severe aortic regurgitation (n=9), left ventricular hypertrophy due to hypertension (n=10). Control group of 20 patients with no history of cardiovascular disease	CT images analyzed in 17 segment model and noncompaction assessed, excluding the LV apex. Ratio of noncompacted to compacted (NC:C) myocardium calculated in each segment	End-diastolic NC:C ratio > 2.3 distinguished LVNC. The sensitivity was 88% and specificity 97%. Positive predictive value = 78%, negative predictive value=99%. The end-diastolic ratio in LVNC patients was 3.44 +/- 0.45 and significantly ($p<0.001$) different from all other groups.	CT using an NC:C ratio of >2.3 distinguished LVNC from other cardiomyopathies and from controls	Receiver operator characteristic analysis used to generate cutoff values and sensitivity and specificity to distinguish LVNC	Retrospective, small cohort.	
Steffel et al.	2011	21617326	Retrospective review	74 subjects	All patients diagnosed with LVNC between 1/1995-11/2008	Primary endpoint: Time to cardiovascular death or transplant. Secondary endpoint: First episode of sustained ventricular arrhythmia or appropriate discharge of implantable cardioverter defibrillator (ICD)	PQ duration, QTc duration, and repolarization abnormalities in the inferior leads were independently predictive of a poor prognosis in LVNC	11% of patients with LVNC died of a cardiovascular cause or underwent heart transplantation (primary outcome measure)	P-wave duration (HR 1.015, 95% CI (0.999–1.032, P=0.067) and QTc duration (HR 1.011, 95%CI 0.999–1.024, P=0.077); non-significant after correcting for LVEF	The specificity of these findings as well as the magnitude of the effects in absolute terms are limited and their clinical value for risk stratification of the LVNC population remains uncertain.	
Stöllberger et al.	2011	21784395	Retrospective cohort	N=144 patients	LVNC patients	Identify incidence and risk factors for stroke or embolism	22 out of 144 patients had a stroke (21) or peripheral embolism (1), with 14 patients having a cardioembolic cause, 5 athetrosclerotic and 3 undetermined cause. Predictors for stroke or embolism were age and hypertension. Of the 14 patients with a cardioembolic cause, 6 had atrial fibrillation, 11 had systolic dysfunction and 4 patients had both.	Cardioembolic cause for stroke or embolism was related to the presence of atrial fibrillation or systolic dysfunction, warranting anticoagulation in these patients.	Groups with and without stroke/embolism compared with Student t tests and Fisher's exact tests	Small number of patients	

CI = confidence interval; CMR = cardiac magnetic resonance imaging; CT = computed tomography; ECG = electrocardiogram; EP = electrophysiologic; HR = hazard ratio; ICD = implantable cardioverter defibrillator; LGE = late gadolineum enhancement; LV = left ventricular; LVEF = left