Recommendations for participation in leisure-time physical activity and competitive sports of patients with arrhythmias and potentially arrhythmogenic conditions. Part 2: ventricular arrhythmias, channelopathies, and implantable defibrillators

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EHRA POSITION PAPER

Recommendations for participation in leisure-time physical activity and competitive sports of patients with arrhythmias and potentially arrhythmogenic conditions. Part 2: ventricular arrhythmias, channelopathies, and implantable defibrillators

A position statement of the Section of Sports Cardiology and Exercise from the European Association of Preventive Cardiology (EAPC) and the European Heart Rhythm Association (EHRA), both associations of the European Society of Cardiology

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Abstract

This paper belongs to a series of recommendation documents for participation in leisure-time physical activity and competitive sports by the European Association of Preventive Cardiology (EAPC). Together with an accompanying paper on supraventricular arrhythmias, this second text deals specifically with those participants in whom some form of ventricular rhythm disorder is documented, who are diagnosed with an inherited arrhythmogenic condition, and/or who have an implanted pacemaker or cardioverter defibrillator. A companion text on recommendations in athletes with supraventricular arrhythmias is published in the European Journal of Preventive Cardiology. Since both texts focus on arrhythmias, they are the result of a collaboration between EAPC and the European Heart Rhythm Association (EHRA). The documents provide a framework for evaluating eligibility to perform

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sports, based on three elements, i.e. the prognostic risk of the arrhythmias when performing sports, the symptomatic impact of arrhythmias while performing sports, and the potential progression of underlying structural problems as the result of sports.

Keywords Sports • eligibility • ventricular arrhythmias • pacemakers • implantable defibrillators

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Introduction

Ventricular tachyarrhythmias obviously create a prognostic threat to the athlete since they may lead to sports-related sudden death. The prevalence of sports-related sudden cardiac death (SCD) in athletes is 2.1/100 000 athletes years.[1] Moreover, ventricular arrhythmias (VAs) may result in symptoms which may create hindrance to continue physical activity and may even result in syncope or presyncope that could compromise the safety of the athlete or other participants. Ventricular arrhythmias may be the final common pathway of other cardiovascular conditions, like hypertension, ischaemic and valvular heart disease, congenital malformations, and dilated cardiomyopathy. These conditions formed the focus of other articles in the updated series on 'Recommendations for Participation'.[2–4] This text deals specifically with athletes in whom some form of ventricular rhythm disorder is documented, or when the patient is diagnosed to have inherited a genetic disorder (channelopathy) that may predispose to VAs. Also, recommendations on sports participation in patients with a pacemaker or an implantable cardioverter-defibrillator (ICD) are discussed in this text. A companion text on recommendations in athletes with supraventricular arrhythmias is published in the *European Journal of Preventive Cardiology*.[5] Both texts update European recommendations from 2005 and 2006.[6–8] The introductory chapters of that first part described the framework for evaluating eligibility to perform sports, based on three elements , i.e. considering the prognostic risk of the arrhythmias when performing sports, the symptomatic impact during sports, and the potential that physical activity might promote progression of underlying structural problems. The same aspects will obviously also be addressed in the different chapters of this text.

As in the supraventricular arrhythmias (SVT) article, the recommendations are formulated using 'coloured hearts'. This grading does not include definitions of the 'level of evidence'. A green heart indicates a 'should do this' recommendation or indicated treatment or procedure that is based on at least one randomized trial, or is supported by strong observational evidence that it is beneficial and effective. A yellow heart indicates general agreement and/or scientific evidence favouring a 'may do this' statement or the usefulness/efficacy of a treatment or procedure. A yellow heart symbol may be supported by randomized trials based on a small number of patients or which is not widely applicable. Treatment strategies for which there is scientific evidence of potential harm and should not be used ('do not do this') are indicated by a red heart.

It is important to note that there remains a paucity of large-scale and/or prospective data on the safety of sports participation with the aforementioned conditions. Therefore, most recommendations represent expert consensus on what is considered appropriate participation in competitive or recreational sports activity. The recommendations mentioned in this paper may also apply to professional working environments demanding more than light physical activity. Clinicians dealing with athletes or patients have to consider these recommendations as guidance for individualized medical advice and shared decision-making in many instances, not as rigid standards or protocols. Factors that have to be taken into account when tailoring recommendations are the type of sports (degree of isometric and isotonic work; low, moderate to high total cardiovascular demand; progressive demand or burst activity), patient motivation, ambient

factors (temperature, humidity), and relevance of any incapacitating situation like dizziness or (pre)syncope (e.g. during sports like diving, driving, mountaineering, etc.). It is also important to realize that often there is no clear distinction between competitive and leisure-time activities, nor between competition and training (with the latter sometimes demanding more strenuous exercise than the competition itself). Patients often ask for quantitative limits of allowed activity (e.g. based on heart rate): however, there is no data to support such quantitative advice, except in the individual case where exercise testing has shown reproducible arrhythmia induction beyond a certain level and never below. Conventionally, exercise at >70% of individualized maximum oxygen uptake (dynamic) or >50% of maximum voluntary contraction (static) is considered 'high intensity'.[9] Several other factors have the potential to influence the impact of an effort on the organism, such as exercise duration, time of the day, weather, temperature, time between training sessions, (de)hydration, and nutrition. This can cause a similar exercise to be light to moderate on one day and intense on another day. As an adjunct, ratings of perceived exertion (RPE, such as the Borg scale) might be used to approximate the relative intensity of any activity.[10,11] An exercise with an RPE of ≥15 is considered high intensive. The use of such scales, however, has its own limitations, and moderate correlations with oxygen uptake variables have been reported.[12]

The physician should also discuss with the patient that systematic or progressive training cannot cure or prevent exercise-related arrhythmias, contrary to the belief of many. In general, patients should even be advised not to pursue progressive training effects in endurance programmes like running or biking (even during non-competitive activity) since these may lead to an insidious increase in work load (with an increased risk for arrhythmia triggering) or a progression of the underlying disease process [e.g. arrhythmogenic cardiomyopathy (AC), see below]. Structured training programmes to achieve ever higher goals and competition should be considered as 'high intensive'.

Documented ventricular arrhythmias

Cardiovascular evaluation, performed during regular follow-up or triggered by symptoms, may reveal VAs on a 12-lead electrocardiogram (ECG), exercise ECG or long-term ECG recording (Holter, event recorder). Many of these documented arrhythmias can be asymptomatic. We will discuss the prognostic significance of such arrhythmias, the need for further work-up, management options, and impact on sports eligibility.

Ventricular premature beats and non-sustained ventricular tachycardia

Most studies have shown that only a minority of athletes exhibit frequent or complex VAs with a prevalence that did not differ with that of their sedentary counterparts.[13–21]

Characteristics of premature ventricular beats

Number and complexity

Holter monitoring is a key test for the evaluation of the 'arrhythmic burden', i.e. the number of premature ventricular beats (VPBs) during 24 h and their tendency to become more 'complex' in the form of couplets, triplets or non-sustained ventricular tachycardia (nsVT). More than 500 VPBs per 24 h is considered a minor diagnostic criterion of AC.[22,23] Biffi *et al.*[20] demonstrated that elite athletes with frequent (>2000/24 h) VPBs and nsVT had a higher probability of an underlying heart disease compared to athletes with rare and isolated VPBs (30% vs. 1.8%; $P < 0.001$). However, a high number of VPBs in itself does not confer an increased risk of malignant events. Ectopic foci located in the right or left ventricular outflow tract (RVOT or LVOT) or in the fascicles of the left bundle branch may give rise to very frequent VPBs (>10 000/24 h) that are usually isolated and occur in the absence of a pathological substrate.[24,25] Very frequent VPBs are associated with a benign prognosis if an underlying disease and tachycardia-mediated left ventricular (LV) dysfunction are excluded.[24,26–29] Therefore, follow-up of LV function is warranted. On the other hand, systematic investigation of SCD in athletes with retrospective evaluation of prior ECG tracings demonstrated that even rare VPBs may be a warning sign of an underlying heart disease in an otherwise asymptomatic individual, and, thus, should not be dismissed as an insignificant finding.[30]

Morphology

The assessment of the morphology of the ectopic QRS complex on surface ECG helps to identify the anatomic origin of the VPBs and to recognize a distinctive category of 'idiopathic' forms, which are characterized by the absence of underlying structural heart disease and a favourable prognosis (*Figure 1*).[31,32] The most common form of idiopathic VPBs show an ECG pattern of 'left bundle branch block (LBBB) + inferior QRS axis' ('infundibular' pattern): negative QRS-complex in lead V1, R/S transition beyond V3 and negative QRS complex in lead aVL. This morphology denotes the origin of VAs from RVOT. A similar morphology but with small R waves in V1 and earlier precordial transition (R/S = 1 by V2 or V3) indicates the origin from the LVOT. On Holter monitoring, the arrhythmia manifests as frequent isolated VPBs and couplets, and even occasional triplets or runs of nsVT may occur. Typically, VAs are transiently suppressed by sinus tachycardia and decrease or disappear during stress testing while re-appearing during recovery.[33] Another morphology of idiopathic VPBs shows an ECG pattern of 'right bundle branch block (RBBB) + superior QRS axis (rarely inferior QRS axis)' morphology and narrow QRS (<130 ms). This 'fascicular' pattern indicates origin from the specialized conduction system, usually the left posterior fascicle of the left bundle branch.[34] Like the infundibular VPBs, fascicular forms often occur in the absence of underlying structural heart disease.[33,34] Another relatively common source of idiopathic VPBs is the mitral valve annulus: VPBs show 'RBBB + inferior QRS axis' morphology with RS pattern in V1, monophasic R or Rs pattern in leads V2–V6, and inferior axis in the limb leads.[35] The majority of competitive athletes (from 68% to 73%) with VPBs in the absence of an underlying disease show VAs with infundibular pattern, followed by fascicular pattern in 15–21%, and 9% with an LVOT pattern. Other morphologies, such as LBBB/superior axis or RBBB/QRS >130 ms are rare.[28,36,37] A study using 12-lead 24-h Holter monitoring conducted in 288 athletes, found that only six athletes showed >500 VPBs/days five with outflow tract morphologic features and one with a fascicular pattern; in four this was associated with ≥1 complex VAs.[18]

Conversely, other morphologies of VPBs, such as LBBB + intermediate or superior axis or RBBB + intermediate or superior axis and wide QRS are uncommon in athletes and when present are

Table 1 Classification of premature ventricular beats in athletes. Any uncommon finding qualifies the VPB as 'uncommon'

	Common Likely benign	Uncommon Potentially malignant
VPBs characteristics		
Morphology	LBBB/inferior axis; RBBB and narrow QRS	LBBB/intermediate or superior axis; RBBB and wide QRS
Response to exercise	Decrease/suppression	Persistence/increase
Complexity	Isolated, monomorphic	Repetitive, polymorphic
Short coupling interval (R on T)	No	Yes
Clinical findings		
Symptoms	No	Yes
Family history of premature SCD[a] or cardiomyopathy	No	Yes
ECG abnormalities	No	Yes
Imaging abnormalities	No	Yes

Adapted from Ref.[51]
ECG, electrocardiogram; LBBB, left bundle branch block; RBBB, right bundle branch block; SCD, sudden cardiac death; VPBs, premature ventricular beats.
[a]Premature SCD or cardiomyopathy is defined as that occurring before 40 years old in males and before 50 years old in females.

usually less numerous, tend to be complex and/or exercise-induced and may be associated with an underlying myocardial disease. Premature ventricular beats with an RBBB-like morphology and wide QRS more often predict the presence of myocardial lesions (particularly non-ischaemic LV myocardial scar) compared with infundibular VPBs.[18,38–41]

Relation to exercise

Premature ventricular beats induced by exercise raise clinical warning because VAs associated with heart diseases are often worsened by adrenergic stimulation.[1,18,39,40,42–45] A higher prevalence of myocardial substrates was found in a cardiac magnetic resonance (CMR) study among athletes with exercise-induced VPBs compared to those with exercise-suppressed VAs (56% vs. 21%).[40] Exercise-induced VAs with an RBBB morphology or complex VAs were the strongest predictors of pathological CMR (odds ratio = 5.3). On the other hand, reduction or disappearance of VPBs with increasing exercise load is typical of idiopathic and benign VAs, particularly those showing an infundibular pattern.[46,47] Exercise-induced isolated or repetitive VPBs with multiple morphologies, especially with beat-to-beat alternating morphologies (so-called 'bi-directional' pattern) are associated with a high risk of effort-related SCD and may be the expression of catecholaminergic ventricular tachycardia (CPVT), which predisposes to adrenergic-dependent VAs which can degenerate into ventricular fibrillation (see section below).[44]

Response to detraining

The available studies do not allow the establishment of the prognostic value of detraining in athletes with VPBs. The evidence is conflicting: some studies have demonstrated reduction or disappearance of VAs with detraining, without relapse on re-training,[48,49] while others have shown that the persistence or reduction of VAs did not differ in athletes who continued training vs. athletes who interrupted sport activity.[50] Moreover, a regression to the mean phenomenon may explain (part of) these findings when those with the most pronounced arrhythmic expression are chosen for later evaluation. Therefore, the prognosis seems to depend on the presence of an underlying pathological substrate and detraining cannot be seen as a simple management strategy.

Evaluation of athletes with premature ventricular beats

According to the number, morphologic pattern, complexity, response to exercise and clinical manifestation, VPBs can be classified as common and likely benign vs. uncommon and potentially malignant because of underlying cardiac pathology (*Table 1* and *Figure 2*).[51] Any uncommon finding qualifies the VPB as 'uncommon', which may indicate underlying structural or electrical anomalies, and hence requires further evaluation. This approach has important implications for the cardiovascular evaluation, risk stratification, and management of the athlete with VPBs, although so far there is a paucity of prospective data on the proportion of athletes in whom potentially malignant underlying disease could be detected by using the approach described below.

Electrocardiography

The ECG is an essential part of the evaluation of athletes with VPBs because concomitant repolarization/depolarization abnormalities may provide important information on a possible underlying cardiomyopathy or channelopathy.[52–54] Athletes with VPBs and concomitant repolarization/depolarization abnormalities require an in-depth cardiovascular evaluation. As described above, 12-lead ECG is extremely useful also for the identification of VPB morphology.

Exercise testing

Exercise testing allows to assess the behaviour of VAs with increasing work-load and may also show other abnormal findings suggestive of

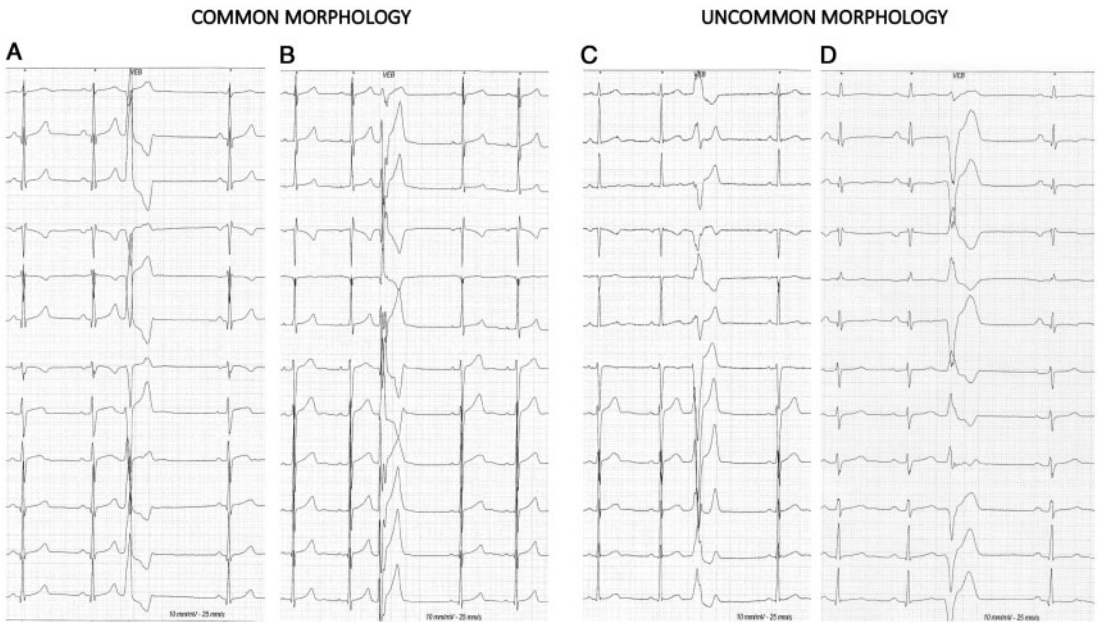

Figure 1 Examples of common (*A* and *B*) and uncommon (*C* and *D*) morphologies of VPBs. (*A*) VPB with LBBB morphology and inferior axis originating from right ventricular outflow tract. (*B*) VPB with RBBB and narrow configuration with superior axis originating from the left fascicles. (*C*) VPB with LBBB morphology and superior axis, originating from right ventricular apex. (*D*) VPB with RBBB and wide QRS configuration with superior axis, originating from the left ventricle. LBBB, left bundle branch block; RBBB, right bundle branch block; VPBs, premature ventricular beats. Adapted from Ref.[51]

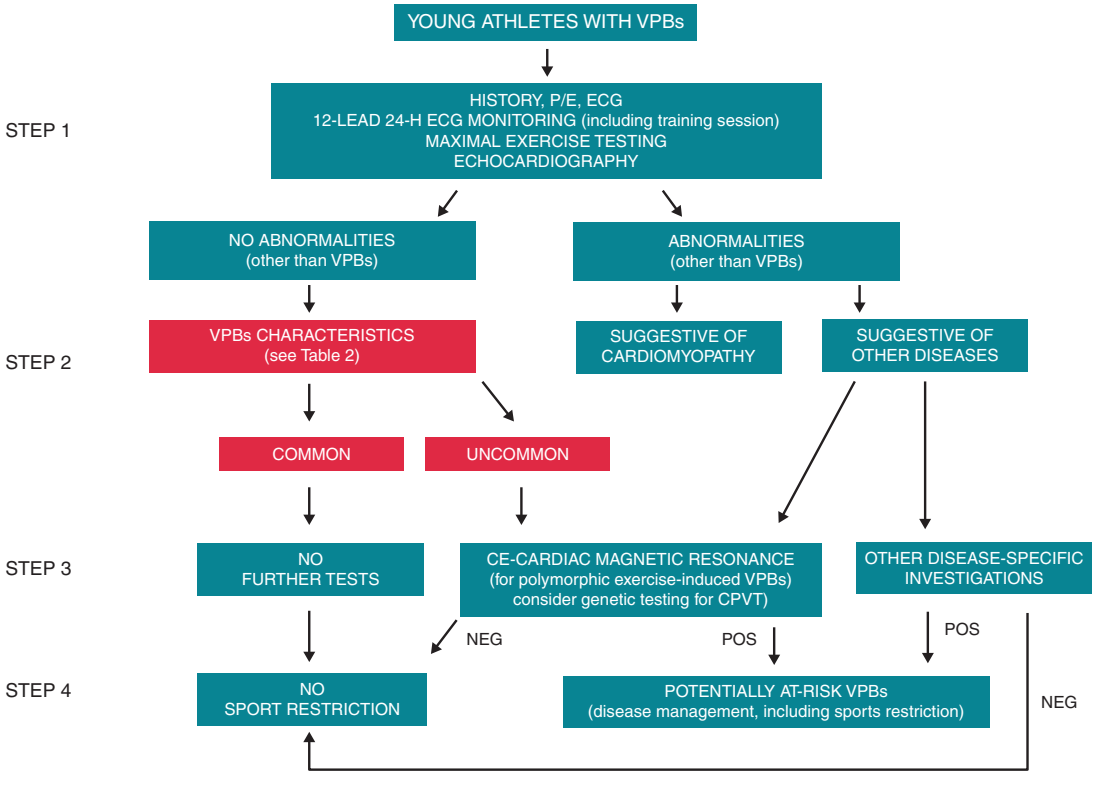

Figure 2 A practical flowchart for clinical evaluation of VPBs in the athlete. CE, contrast-enhanced; NEG: negative; P/E, physical exam; POS, positive; VPB: ventricular premature beats. Adapted from Ref.[51]

an underlying cardiac disease such as ST-segment changes (ischaemia), abnormal blood pressure response (hypertrophic cardiomyopathy, HCM), or impaired exercise capacity (cardiomyopathy; possibly also based on respiratory gas analysis). Exercise testing should not be stopped at the 85% of theoretical maximal heart rate but continued until the athlete is exhausted in order to increase the test sensitivity.[55]

Echocardiography

Echocardiography represents the first imaging test for investigating the presence of a structural heart disease in athletes with VPBs. Echocardiography aims to assess the systolic and diastolic function, ventricular hypertrophy, wall motion abnormalities, and valvular function. Moreover, echocardiography is recommended as the basal screening modality for identification of coronary artery origin anomalies which is a leading cause of ischaemia-induced VAs and SCD in athletes.[56–59] However, echocardiography has no ability to detect some life-threatening conditions such as myocardial bridging, coronary stenosis, or segmental subepicardial-mediomural myocardial fibrosis.

Cardiac magnetic resonance

Beyond the accurate evaluation of cardiac size, function, and regional wall motion abnormalities, CMR has the unique power to identify and quantify myocardial tissue abnormalities, such as oedema, fatty infiltration, or replacement-type fibrosis.[41] Cardiac magnetic resonance identified the presence of non-ischaemic LV scar in a sizeable proportion of athletes with apparently unexplained VPBs, complex VAs or repolarization abnormalities.[18,19,38,40,41,60] As a consequence, CMR has become a key test for the evaluation of athletes with VPBs even if the echocardiography is negative or inconclusive, particularly if the ectopic QRS is wide and shows an RBBB + superior axis pattern, suggesting the origin from the lateral LV wall, and VPBs are repetitive and/or exercise-induced.[40]

Flowchart for management of athletes with premature ventricular beats

The international criteria for ECG interpretation in athletes suggest that further evaluation is warranted when ≥2 VPBs are recorded on a resting 12-lead ECG. Even a single VPB may deserve attention, especially in the presence of one or more of the following features: (i) high-level endurance athletes, (ii) a positive family history of premature SCD or cardiomyopathy, (iii) relevant symptoms, (iv) associated ECG abnormalities, (v) uncommon VPB morphology (*Table 1* and *Figure 1*), and (vi) a short coupling interval.

Figure 2 reports a practical flowchart for management of athletes with VPBs. While further tests in athletes with abnormal first-line examinations depend on the disease that is suspected, the work-up of athletes with negative results depends on the morphology of VPBs. Athletes with common VPB patterns can be considered eligible for competitive sports, unless the clinical suspicion of disease is high (e.g. serious arrhythmic symptoms and/or positive family history for SCD/cardiomyopathy). Athletes with an uncommon morphology of VPBs and/or complex or exercise-induced VPBs should undergo a contrast-enhanced CMR, regardless of symptoms or familial background, to rule out a concealed myocardial substrate at risk of malignant arrhythmic events during sports activity. Other examinations such as coronary computed tomography (CT) or coronary angiography may be considered in selected populations (e.g. athletes with high coronary risk score). Further diagnostic evaluation with sophisticated and costly imaging tests or molecular genetic testing is limited to the small subset of athletes with uncommon VPB characteristics. Furthermore, the arrhythmogenic effects of illicit drugs should be taken into account as a potential cause of arrhythmias in athletes.[61]

Benign and asymptomatic VPB do not require treatment if underlying cardiac disease is excluded. In symptomatic athletes, medical therapy with beta-blockers (if allowed) or Class 1 drugs can be considered, although ablation of the ectopic focus may constitute a more definitive treatment option.

Consensus statements—VPBs and nsVT	Symbol
Athletes with ≥2 VPBs on a baseline ECG (or ≥1 VPB in case of high-endurance athletes, or positive family history of premature SCD or cardiomyopathy, relevant symptoms, associated ECG abnormalities, uncommon VPB morphology, and/or short coupling interval) should undergo thorough evaluation to exclude underlying structural or arrhythmogenic conditions. This includes a detailed familial history taking.[52]	
Testing includes 12-lead ECG (morphology suggestive of common and likely benign, or uncommon and potentially malignant VPB forms), 24-h Holter monitoring possibly with a 12-lead system and including a sports session (morphology, number, and complexity of VBPs), exercise test (increase or decrease with exertion), and suitable imaging (echocardiography and CT and/or cardiac magnetic resonance imaging, MRI).	
If no indication of familial or structural underlying disease, all competitive and leisure-time sports activities are allowed.	
Athletes with a high prevalence of asymptomatic VPBs (in absence of structural heart disease) should be re-evaluated annually (particularly in case of children and adolescents) in order to identify potential changes in the arrhythmic burden and in underlying cardiac condition.	
In symptomatic athletes without structural heart disease, medical treatment for VPB may be an option. Transcatheter ablation may represent the most appropriate therapeutic approach in these subjects.	

Sustained ventricular tachycardia

Documentation of sustained VT requires stringent evaluation to distinguish idiopathic VT from potentially life-threatening monomorphic VTs related to structural heart disease. Polymorphic VTs and VTs with alternating complexes ('bi-directional VT') during exercise are often associated with structural disease or inherited electrophysiological disorder and carry a high risk of malignant events.[62]

Idiopathic, monomorphic sustained VTs are considered benign. However, symptoms [dizziness, (pre)syncope)] depend on VT cycle length (CL) and vascular tone.

Twelve-lead ECG QRS assessment of VT allows identification of the site of origin (see Ventricular Premature Beats and Non-Sustained Ventricular Tachycardia). The majority of focal idiopathic VT are due to triggered activity and arise from the endocardial outflow tract region (RVOT ≫ LVOT) with a repetitive pattern at low levels of exercise and suppression at higher levels. Occasionally exercise-induced sustained VTs occur.[63] However, focal, idiopathic right, and left ventricular non-outflow tract VTs have been recognized. Epicardial idiopathic VT arising from the crux of the heart are due to a focal, catecholamine sensitive mechanism and are often rapid under catecholaminergic stimulation, producing syncope.[64] Idiopathic verapamil-sensitive, left fascicular reentrant VT (left posterior ≫ left anterior ≫ upper septal type) are recognized by the typical ECG and often present as sustained VT.[65] Many of these are also catecholamine-dependent.

Identifying the specific VT mechanism (triggered activity, automaticity, and re-entry) has diagnostic and therapeutic implications. Although the mode of onset of VT documented on Holter recordings or during exercise testing can be helpful, differentiation often requires an invasive electrophysiology study.

Evaluation of athletes with sustained ventricular tachycardia

For general assessment of athletes with VAs (see Ventricular Premature Beats and Non-Sustained Ventricular Tachycardia). Late contrast-enhanced CMR (CE-CMR) should be performed in particular for non-fascicular VT morphologies, even if echocardiography is negative. Distinguishing idiopathic RVOT-VT from early AC affecting the RVOT and exercise-induced arrhythmogenic remodelling (EI-AR) with isolated subepicardial RVOT scar can be particularly challenging.[66] Suspicion for the latter is high if ≥2 distinct VT morphologies with typically fast heart rates are observed in high-level endurance athletes.[43,66,67]

Interventional treatment

Catheter ablation of idiopathic VT is often effective[68] but close follow-up is warranted, since some athletes may have underlying concealed cardiac disease which will only manifest itself over time.

Although ablation of scar-related VT can also be successfully performed with favourable long-term outcome, in particular, in patients with EI-AR,[66] there are no data to indicate that resumption of athletic activity after successful ablation is safe, since the underlying substrate likely is still present. In addition, intensive endurance training may increase the penetrance and arrhythmic risk in AC and may cause or aggravate exercise-induced arrhythmogenic remodelling in the absence of mutations.[66,69] Accordingly, these athletes should not participate in most competitive and recreational sports.

Implantation of an automatic ICD in athletes with sustained VT and structural heart disease or channelopathies should follow current guidelines for secondary prevention of SCD.[62]

Consensus statement—sustained VT	Symbol
Sustained VT disqualifies for competitive sports except for the particular case when all of the following apply: (i) absence of familial sudden death, (ii) no indication of any underlying structural pathology or channelopathy, (iii) a typical presentation of focal or fascicular idiopathic VT, and (iv) no symptoms of haemodynamic compromise during VT with/without exercise.	
Catheter ablation of symptomatic focal idiopathic RVOT VT and idiopathic left fascicular re-entrant VT can be performed with high success rates (80–95%) and with low complication rates and is recommended in athletes to allow resumption of competitive sports.[68]	
Athletes with idiopathic, monomorphic VT, without haemodynamic compromise during exercise, can resume competitive or leisure-time athletic disciplines in which syncope does not lead to an enhanced risk for athlete or others (enhanced risk during e.g. driving, climbing, diving).	
Athletes with idiopathic, monomorphic VT who have undergone successful VT ablation and are without any symptoms or other sign of recurrence (on Holter or exercise test) during a 3-month follow-up period, can resume full competitive or leisure-time athletic activity.	
Symptomatic athletes with ≥2 distinct VT morphologies or VT highly suspicious for reentry as underlying mechanism with negative imaging studies, including CE-CMR, should undergo invasive EP study to assess inducibility of VT and confirm re-entry as underlying mechanism and electroanatomical unipolar and bipolar voltage mapping to identify concealed substrates.	
Athletes with idiopathic, monomorphic VT who choose to undergo drug treatment for suppression and are without any symptoms during a 3-month follow-up period, including exercise testing or EP study, may resume full competitive or leisure-time athletic activity.	
Ablation of idiopathic VT from non-fascicular and non-outflowtract locations, in particular, epicardial sources may involve greater procedural complexity and procedural risks and lower success rates but should be considered dependent on athletes' preference.	
Athletes with structural heart disease or channelopathies and sustained VT should not participate in intense recreational and competitive sports regardless of the acute therapeutic response to ablation/drug treatment.	

Ventricular fibrillation/resuscitated sudden death

Unless a reversible condition can be treated, athletes will qualify for implantation of an ICD. Identifiable and treatable, reversible causes encompass (i) atrial fibrillation with rapid conduction over an accessory pathway which is subsequently successfully ablated, (ii) electrolyte imbalance due to a transient cause, (iii) proarrhythmic drug reactions (e.g. acquired QTc prolongation due to e.g. psychotropic medication), (iv) transient ischaemia without myocardial infarction (MI), which is followed by complete revascularization,[70] (v) transient ischaemia without MI due to coronary arterial vasoconstriction in response to cocaine, and (vi) acute myocarditis, followed by normalization of cardiac function, serum markers of inflammation/myocardial injury and absence of frequent and complex ectopy. Whether absence of (post)myocarditis late gadolinium enhancement (LGE) on CMR imaging should be required is a matter of discussion. After complete resolution of myocarditis sequellae is confirmed (including absence of any inducible arrhythmias during exercise or EP study in case of residual LGE), resumption of competitive sports can only be considered after a 3- to 6-month period.[39,71]

It should be noted that patients may remain at higher risk for sudden death, even after resolution of the transient cause (especially when it is ischaemic in origin).[72] In addition, concealed forms of channelopathies need to be considered (see specific sections).

Consensus statement—ventricular fibrillation/resuscitated sudden death	Symbol
In athletes with a resuscitated sudden death reversible conditions should be defined and treated.	♥
In athletes without definitive guarantee that a resolved transient cause of resuscitated sudden death will never recur; competitive sports are contra-indicated.	♥

Arrhythmias in the context of known ischaemic heart disease

Ventricular arrhythmias are a marker of worse prognosis and in ischemic heart disease (IHD) are evaluated by resting and Holter ECG or if necessary, by wearable or implantable loop recorder. If dizziness or syncope occurs, physical activity should be restricted until medical assessment. In case of documented non-sustained VTs (≥3 VPBs), exercise should be limited to non-competitive sports.[4] Presence of myocardial ischaemia has to be localized and quantified by appropriate methods (e.g. ergometry, stress echocardiography, exercise stress myocardial perfusion scintigraphy, perfusion MRI) to guide strategies of revascularization and to step-up medication with the aim to eliminate ischaemia.[70]

IHD patients without ischaemia, non-sustained or sustained arrhythmias, who are considered low risk for cardiac events, can perform competitive sports without restrictions but with close follow-up.[4] In case of ischaemia and/or arrhythmia despite optimal medication and revascularization, patients are considered high risk. Nonetheless, exercise training at a non-competitive level is still recommended, since it has been shown to slow progression of coronary atherosclerosis,[73–75] and improve morbidity and mortality.[76] Recommendations for individually tailored exercise prescription and participation in leisure time or competitive sports in IHD have been published by the *European Society of Cardiology*.[4,77]

Once ischaemia and arrhythmias have been treated successfully, annual follow-up is sufficient and should include as a minimum patient history, physical examination, risk factor analysis, resting ECG, and diagnostic procedures to identify or rule out ischaemia and/or arrhythmia, i.e. exercise-testing, stress echocardiography, stress scintigraphy, and/or perfusion CMR imaging as chosen appropriate.

Consensus statement—arrhythmias in the context of known ischaemic heart disease	Symbol
In case of ischaemia with or without VT, despite optimal medication and revascularization, only non-competitive sports are allowed.	♥
Without ischaemia and without VT, i.e. low-risk patients, there are no restrictions for competitive sports.	♥
Annual follow-up is recommended in any athlete with known ischaemic heart disease.	♥

Arrhythmias in the context of inherited arrhythmogenic conditions

A number of familial arrhythmogenic conditions have been characterized over the last decades as underlying causes for arrhythmias and sudden death in athletes,[78,79] and in the near future this number will grow.

Contemporary approach to phenotyping, cascade screening, and genotyping

It is well established that high-level physical exertion in patients with inherited arrhythmogenic diseases may aggravate the underlying condition and precipitate cardiac arrhythmias and SCD.[80–82] The diagnosis of most inherited arrhythmogenic conditions is based on clinical evaluation, personal, and family history. Due to variable clinical expression such conditions may remain undetected leaving many unaware and exposed to the exertion-associated elevated risk.

Cardiovascular pre-participation evaluation (PPE) as advocated by the ESC encompasses medical history, physical examination, and a 12-lead ECG to detect pre-existing cardiac conditions.[53] Upon

positive findings, additional testing, such as echocardiography, stress testing, CMR imaging, and 24-h Holter monitoring may be indicated.

When the presence of inherited arrhythmogenic disease is suspected, the athlete and his family should be referred to a dedicated inherited cardiovascular disease clinic where structured phenotyping, risk stratification and management is provided to all consenting relatives.[83–89] A detailed pedigree is assembled with all available data on the phenotype and genotype of each relative. In line with known/observed inheritance patterns, a cascade screening approach is initiated, starting with the athlete and his first-degree relatives (FDR), cascading further down to their next of kin.

Next to risk stratification, the screening of first-degree relatives may be useful to further define the familial phenotype and observe its heterogeneity. However, in the perspective of complex variable expressivity and often incomplete penetrance the timing and decision to investigate FDRs must always be weighed carefully against potential harm that may be inflicted as it may have grave impact on lifestyle, anxiety levels, and psychological burden.[90]

Genotyping to identify the underlying molecular defect is useful as it may provide confirmation of the clinical diagnosis in the athlete and allows the identification of affected family members in a pre-symptomatic state.[91–93] The yield of genetic testing as well as the diagnostic, therapeutic, and prognostic significance in each of the inherited diseases will be discussed in the following sections.

Genetic screening in healthy individuals without (family) history and normal PPE is not recommended since variants of unknown significance (VUS) may be revealed that reflect evolutionary genetic diversity. Incorrect interpretation of VUS can lead to medical overconsumption and erroneously affect eligibility for sport participation.[90] Therefore, with the exception of Sudden Unexplained Death Syndrome where genetic screening has become the cornerstone of the molecular autopsy, the decision to genotype should primarily be driven by the phenotype that was established previously in the athlete or in a first-degree relative as part of cascade screening.[91,94–99]

With the advent of next generation sequencing techniques, preselected gene panels and whole exome/genome sequencing are available with high sensitivity and specificity and with reasonable turnaround times. There is recent evidence that copy number variations (CNVs) play a role in the pathogenesis of inherited arrhythmogenic conditions. Additional techniques to detect CNVs should be included in routine genetic testing.[100]

Sequence analysis and interpretation should be performed in compliance with proposed standards for variant interpretation, adopting five classes of pathogenicity: (i) benign, (ii) likely benign, (iii) uncertain significance, (iv) likely pathogenic, and (v) pathogenic.[101]

It should be noted that acquired factors, non-penetrance, variable, and late manifestation of the phenotype as well as oligogenic rather than monogenic disease architecture may further complicate linkage analysis. Although clear guidelines exist, intense scrutiny should be upheld when classifying variants and assigning potentially life-changing clinical consequences to molecular data.[102,103] This requires experienced multidisplinary units specialized in variant interpretation and classification, based on all gathered genetic and phenotypical data. Classification is a continuous process open to revision and reclassification based on newly emerging genotype-phenotype correlation data from further cascade screening.[104]

Consensus statement—approach to phenotyping, cascade screening and genotyping	Symbol
Suspected inherited arrhythmogenic disease should be assessed in a dedicated cardiogenetics clinic, including cascade screening.	
Genotyping to identify the underlying molecular defect is useful to confirm clinical diagnosis in the proband and allows pre-symptomatic identification of affected family members.	
Sequence analysis and interpretation should be performed in compliance with proposed standards for variant interpretation, adopting five classes of pathogenicity.	
Cardiac screening of first-degree relatives may be useful for risk stratification and to further define the familial phenotype.	
Genetic screening in healthy individuals without (family) history and normal PPE is not recommended	

Long QT syndrome

Long QT syndrome (LQTS) can be suspected on a routine ECG if the corrected QTc interval according to Bazett's formula is ≥470 or ≥480 ms in asymptomatic male or female athletes respectively.[52,105] The diagnosis can be corroborated based on clinical criteria (*Table 2*).[106,107] A QTc of ≥500 ms is diagnostic.[108] Details on how to measure the corrected QTc interval in athletes and the upper normal values were published in the 2018 'International recommendations for electrocardiographic interpretation in athletes'.[52] Congenital LQTS should be distinguished from acquired forms, i.e. due to circumstances, which can be reversed and prevented. Once acquired LQTS is established, sports activity should be prohibited until factors, such as QT-prolonging drugs have been stopped and potential electrolyte disturbance have been corrected.

Whenever LQTS is suspected, the following should be done: a careful clinical history of proband and family, a baseline ECG, an exercise stress test (focusing on T wave changes during recovery and the QTc interval after 4 min of recovery which, if ≥30 ms longer than at baseline, suggests LQTS),[109] and a 24-h Holter recording (preferably a 12-lead type since diagnostic patterns are often seen only in precordial leads).

Genetics have become essential for management. Therefore, genetic testing should be performed when available in all athletes with suspicion of LQTS. A large proportion of LQTS gene carriers, especially with LQT1, may have a borderline QT prolongation.[110] The risk of cardiac events during sport activities is largely gene-specific. LQT1 patients, with a reduction in the I_{Ks} current which impairs the normal QT shortening during heart rate increases, are at highest risk

Table 2 Diagnostic criteria for long QT syndrome

			Points
Electrocardiographic findings[a]			
A	QTc[b]	≥480 ms	3
		460–479 ms	2
		450–459 (male) ms	1
B	QTc[b] 4th min of recovery from exercise stress test ≥480 ms		1
C	Torsade de pointes[c]		2
D	T-wave alternans		1
E	Notched T wave in three leads		1
F	Low heart rate for age[d]		0.5
Clinical history			
A	Syncope[c]	With stress	2
		Without stress	1
B	Congenital deafness		0.5
Family history			
A	Family members with definite LQTS[e]		1
B	Unexplained sudden cardiac death below age 30 among immediate family members[e]		0.5

Score: ≤1 point: low probability of LQTS; 1.5–3 points: intermediate probability of LQTS; ≥3.5 points high probability of LQTS. Adapted with permission from Ref.[107]
LQTS, long QT syndrome.
[a]In the absence of medications or disorders known to affect these electrocardiographic features.
[b]QTc calculated by Bazett's formula where QTc = QT/$\sqrt{}$RR.
[c]Mutually exclusive.
[d]Resting heart rate below the 2nd percentile for age.
[e]The same family member cannot be counted in A and B.

during stressful exercise.[111] Moreover, a *de novo* disease-causing mutation carries a more uncertain arrhythmic risk (no family history).

Sudden death is often the sentinel event and >60% of cardiac arrests occur in previously asymptomatic subjects. This has two implications: (i) being asymptomatic until age 18–20 years is no guarantee of low risk; (ii) once LQTS has been diagnosed, therapy should start without hesitation.[106] General precautions include avoidance of QT-prolonging drugs, dehydration, and electrolyte imbalance. Beta-blocker therapy is extremely effective, although the basal heart rate in athletes may limit the dose. There is a preference for nadolol or propranolol which are more effective than other beta-blockers.[106]

Long QT syndrome patients who already had a cardiac arrest should receive an ICD.[62] For patients with an LQTS-related syncopal episode while on beta-blocker therapy, either an ICD or left cardiac sympathetic denervation should be considered.[112] If ICD is contraindicated or refused, left cardiac sympathetic denervation should be considered.[62]

Athletes with LQTS and prior cardiac arrest or arrhythmic syncope should not be allowed to practice competitive sports. Implantable cardioverter-defibrillator implantation does not constitute a clearance for intensive or competitive sports. Continued sports participation with an ICD is possible, but specific recommendations apply (see below section Implantable cardioverter-defibrillators).

Electrocardiographically manifest LQTS patients, even when asymptomatic and on treatment with beta-blockers and other precautionary measures should not be considered eligible to practice in more than light- to moderate intensity recreational sport disciplines. American guidelines are more lenient in this respect (except for LQT1), provided that precautions include the presence of an automatic external defibrillator (AED) 'as part of the athlete's personal sports safety gear'.[113] We consider such obligation impractical to impossible (e.g. winter sports; water sports), and it puts responsibilities on clubs or other bystanders which cannot be justified by a medical recommendation for an individual athlete. Moreover, although LQTS-related cardiac arrest is uncommon during competitive sports,[114] AED efficacy is not 100% in such cases.[115] On the other hand, the presence of AED may be considered by the athlete when choosing a sport facility/gym/arena to participate in leisure-time sports.

In asymptomatic LQTS mutation carriers without a prolonged QT interval, i.e. <470/480 ms in men/women ('genotype positive/phenotype negative') shared decision-making is required, balancing the risk for arrhythmias (mainly based on the known genotype) vs. psychological well-being. A negative exercise stress test has no predictive value because arrhythmias are usually triggered by the combination of physical exercise and emotional stress. Team sports are more dangerous for LQTS patients than solo sports, in which the athlete can decide if and when to slow down. Moreover, there can be more psychological stress in a team environment, acting as an arrhythmia-triggering factor. Low-intensity competitive sports are preferred over high-intensity sports, certainly for LQT1 patients. The risk of cardiac events during physical activity is relatively modest for LQT2 and LQT3 patients, allowing more flexibility in allowing them to practice sports. In other, rarer, forms of LQTS, close discussion with cardiogenetics experts is required to evaluate the relationship of the subform with arrhythmias from available literature data. LQT1 patients should swim in a supervised pool and avoid diving before being acquainted to the temperature of the water. Sudden unexpected auditory stimuli may trigger polymorphic VT in patients with the LQT2 subtype.[111]

Consensus statement—congenital LQTS	Symbol
All LQTS athletes should avoid QT prolonging drugs (www.crediblemeds.org) and electrolyte imbalance like hypokalaemia and hypomagnesemia (potassium supplementation is recommended before taking part to sports activity).	
All LQTS athletes with prior symptoms or prolonged QTc should be on therapy with beta-blockers at target dose.	
Athletes with LQTS and prior cardiac arrest or arrhythmic syncope should not be allowed to practice competitive sports (with or without ICD).	
Athletes with a QTc >500 ms, a de novo disease-causing mutation (especially if LQT1), or genetically confirmed LQTS with a QTc ≥470 ms in men or ≥480 ms in women should not practice more than light- to moderate intensity recreational sports, even when on beta-blockers.	
Recommendations to sports participation require open discussion with the athlete and their entourage, finding a balance between life protection and quality of life during shared decision-making.	
It is reasonable to allow individual sports at low to moderate intensity for asymptomatic athletes with an LQT1 mutation but QTc <470/480 ms and who are on prophylactic beta-blocker therapy, but team sports and high-intensity sports are discouraged.	
It is reasonable to allow all types of sports participation for asymptomatic athletes with an LQT2 or LQT3 mutation but QTc <470/480 ms, and who are on prophylactic beta-blocker therapy.	
For asymptomatic athletes with other LQTS mutations and QTc <470/480 ms, cardiogenetics consult and shared decision-making are required.	

Short QT syndrome

The short QT syndrome (SQTS) is a very rare disease described just 20 years ago.[116] So far, only slightly more than 100 patients have been described worldwide. The clinical presentation tends to be quite severe, with a high incidence of cardiac arrest and sudden death.[117] The diagnostic criteria are not yet firm and require either a QTc ≤340 ms or a QTc between 341 and 360 but with an associated history of life-threatening arrhythmias or a family history for SQTS or for sudden death before age 40, as well as atrial fibrillation.[118–120] Moreover, the diagnosis based on the QTc interval is dependent on the QTc correction formula, the prediction accuracy of which requires further assessment.[121] There is an overwhelming predominance of male patients. While no specific triggers for arrhythmic episodes have been identified in the European Short QT Registry,[118] one report indicated that most episodes of cardiac arrest occurred at rest/sleep and just 15% during emotions or exercise.[120] Current therapy is based on either quinidine or ICD, both burdened by significant limitations[117] The protective effect of quinidine during exercise is unknown. Thus, it should be clear that there is no ground for solid recommendations regarding sports activity. Given the clinical severity and the (rare) occurrence of events during exercise, it may be desirable that patients with SQTS should not practice sports activity with the possible exception of some leisure activity.

Consensus statements—congenital short QT syndrome	Symbol
It is recommended to restrict all athletes with SQTS, diagnosed or suspected, from all competitive sports.	
It is reasonable to allow light to moderate leisure sport activity to asymptomatic SQTS patients without family history of SCD.	

Brugada syndrome

The Brugada syndrome (BrS) is an inherited condition associated with an elevated risk of ventricular fibrillation (VF) and SCD in young individuals with a structurally normal heart.[122,123] This disease presents with an autosomal dominant pattern of inheritance with incomplete penetrance and variable expressivity.[123] More than 500 pathogenic genetic variants have been described, mostly located in the SCN5A gene.[124] Unfortunately, a pathogenic variant is only found in 25–30% of individuals.[125–127] Although BrS was initially described as a purely electrical disease, minor structural abnormalities may sometimes be observed.[128–131]

The true prevalence of BrS is unknown due to the dynamic nature of the ECG pattern, which is frequently inapparent.[132] It shows a male predominance.[133–135] BrS typically manifests in adulthood, but it can also occur in children and the elderly.[136–139] Most patients are asymptomatic at the time of evaluation and remain so throughout their lives. In symptomatic patients, the majority of events occur during sleep or rest, during febrile states or, occasionally, from heat stroke.[140–147] The conduction defects explain why some may develop VAs during exercise.[148] Also, exercise may unmask the typical type 1 Brugada pattern in patients with non-diagnostic ECGs,[149–153] and during/immediately after exercise, ST-segment augmentation may be observed (*Figure 3*).[149–160]

Diagnosis is made when a type 1 Brugada pattern is observed (coved-type ST-segment elevation ≥2 mm followed by a negative T wave in ≥1 of the right precordial leads positioned in the 4th, 3rd, or 2nd intercostal space), either spontaneously or during a sodium-channel blocker test, once all other known causes of ST-segment elevation have been ruled out, including acute myocardial ischaemia or infarction, acute myocarditis, Prinzmetal angina, dissecting aortic aneurysm, acute pulmonary thromboemboli, Duchenne muscular dystrophy, Friedreich ataxia, mediastinal tumour compressing the right

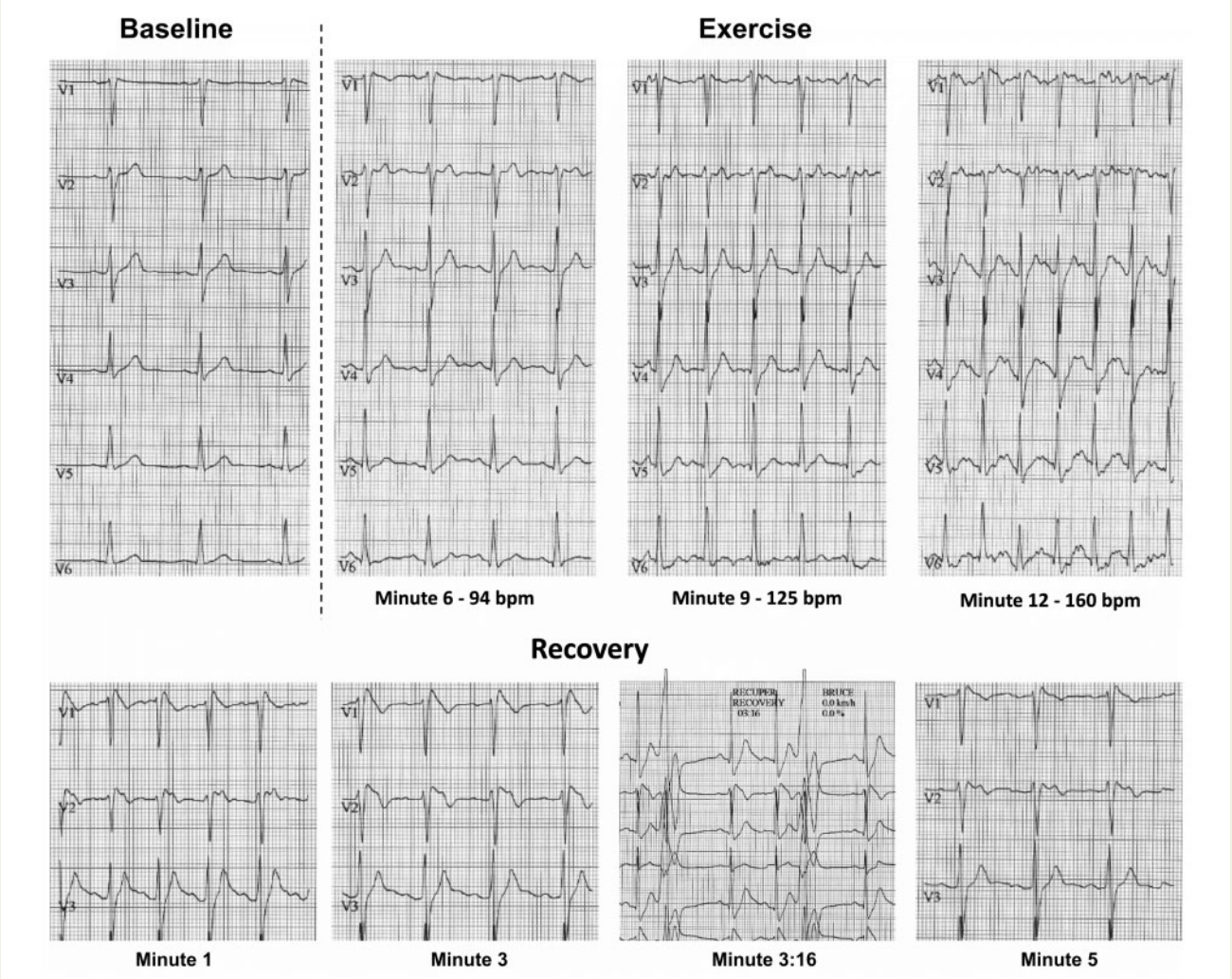

Figure 3 Stress test in a patient with Brugada syndrome. At baseline, a normal ECG is observed, with no precordial ST-segment elevation. During exercise, the right precordial leads show a mild ST-segment elevation and gradual T-wave negativation. During recovery, the Brugada Type 1 pattern becomes evident and ventricular premature contractions occur. After 5 min of observation, the Brugada pattern and the ventricular ectopy disappears. ECG, electrocardiogram.

ventricular outflow tract, arrhythmogenic right ventricular cardiomyopathy, etc. (*Figure 4*).[161–163] In some cases, it may be difficult to distinguish the BrS ECG from the non-pathological electrical remodelling in athletes, which can include the presence of incomplete right bundle branch block, ST-segment elevation/early repolarization, and T-wave inversion in right precordial leads, mimicking the Brugada pattern.[52,164] For the differential diagnosis, it is useful to analyse the ST-T waveform. Athletes show an upsloping ST-segment with a mean STJ/ST80 ratio ≤1, whereas BrS patients show a downsloping ST-segment with a STJ/ST80 ratio >1.[54] When in doubt, it is sometimes useful to perform a drug challenge with a sodium channel blocker. Other unspecific ECG findings in BrS which are also common after long-term sport training include sinus node dysfunction,[165–167] P wave, PR and QRS prolongation,[148,168,169] and supra-VAs (mainly atrial fibrillation).[148,170–173]

Symptomatic patients (SD and/or syncope, particularly in the presence of spontaneous type 1 Brugada pattern) should undergo ICD implantation.[62,174] Quinidine or catheter ablation is recommended in patients with recurrent VAs or when ICD implantation is not an option.[62,174] In asymptomatic patients with only inducible type 1 Brugada ECG pattern, only preventive measures are recommended, like avoidance of triggering drugs (www.brugadadrugs.org), electrolyte unbalance, and increases in core temperature >39°C (e.g. by minimizing immersion in hot tubs, saunas and steam rooms; by avoiding sporting in warm/humid conditions; or by abstaining from prolonged endurance events such as triathlon and marathons). During febrile illness, fever should be treated aggressively.[62,174] Risk stratification in the asymptomatic population with spontaneous type 1 ECG pattern is more challenging. In this group of patients, electrophysiological study with programmed ventricular stimulation may be considered for risk stratification.[62,174]

Theoretically, an enhanced vagal tone at rest[175] might increase the susceptibility of high-level athletes to die at rest but there is no data to support such association. In general, there is a scarcity of large prospective studies evaluating the effect of exercise and sport in BrS and no reports are available directly associating physical activity to cardiac events. Therefore, asymptomatic BS patients, phenotypically-

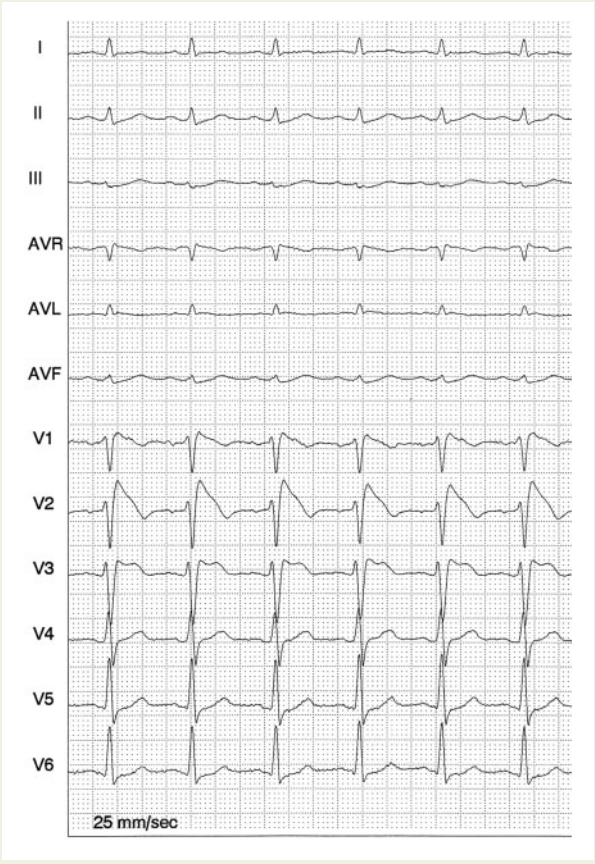

Figure 4 Diagnostic Brugada type 1 pattern showing ST-segment elevation ≥2 mm followed by a negative T wave in ≥1 of the right precordial leads.

negative BrS mutation carriers or those with only an inducible ECG pattern can compete in all sports that are not associated with an increase in core temperature >39°C (which should be checked during training sessions).

For symptomatic BrS patients (syncope and/or aborted SCD), ICD implantation is recommended. After ICD implantation, if asymptomatic for ≥3 months and when paying attention to precautionary measures (i.e. avoidance of drugs, fever, heat stroke), all sports (also competitive) can be considered after shared decision-making, considering the findings from the Sports ICD Safety Registry (see below).

Catecholaminergic polymorphic ventricular tachycardia

Catecholaminergic ventricular tachycardia is a highly lethal primary cardiac electrical disease (typically before age 20–30 years), characterized by complex VAs (classically, bidirectional VT) triggered by adrenergic stimuli (typically, emotional stress, or exercise), leading to syncope or SCD (*Figure 5*).[176,177] This clinical entity may comprise 5–10% of patients with familial arrhythmias but without QTc prolongation or Brugada type ECG abnormalities.[178] Currently, the genetic cause is identified in 65% of patients with a clinical diagnosis.[179] Most cases are secondary to autosomal dominant mutations in the RyR2 gene (the calcium release channel of the sarcoplasmic reticulum) or, less frequently, to autosomal recessive mutation in CASQ2 (another protein involved in intracellular calcium handling).[180–184] Mutations in either gene lead to abnormal calcium release from the sarcoplasmic reticulum that is more pronounced in high beta-adrenergic states.[182,185] Other genes, including TRDN, ANK2 (also referred to as LQT4-syndrome), TRD, and KCNJ2 are involved in a minority of cases.

The prevalence of CPVT is roughly estimated to be 1/10 000,[186] but there is no systematic population study to confirm it. When

Consensus statement—Brugada syndrome	Symbol
In BrS patients with episodes of suspected arrhythmic syncope and/or aborted SCD, ICD implantation is recommended.	
In all patients with overt BrS and in all phenotypically-negative mutation carriers, avoidance of drugs that may aggravate the BrS (www.brugadadrugs.org), of electrolyte imbalance, and of increases in core temperature are recommended. In case of febrile illness, fever should be treated aggressively.	
If there is no recurrent event during 3 months in symptomatic BrS patients after ICD implantation, leisure or competitive sports may be resumed based on shared decision-making.[a]	
Asymptomatic BrS patients, asymptomatic mutation carriers, and asymptomatic athletes with only an inducible ECG pattern, may participate in all sports that are not associated with an increase in core temperature >39°C (e.g. endurance events under extremely hot and/or humid conditions).	

[a]Avoid contact sports in case of ICD implanted.

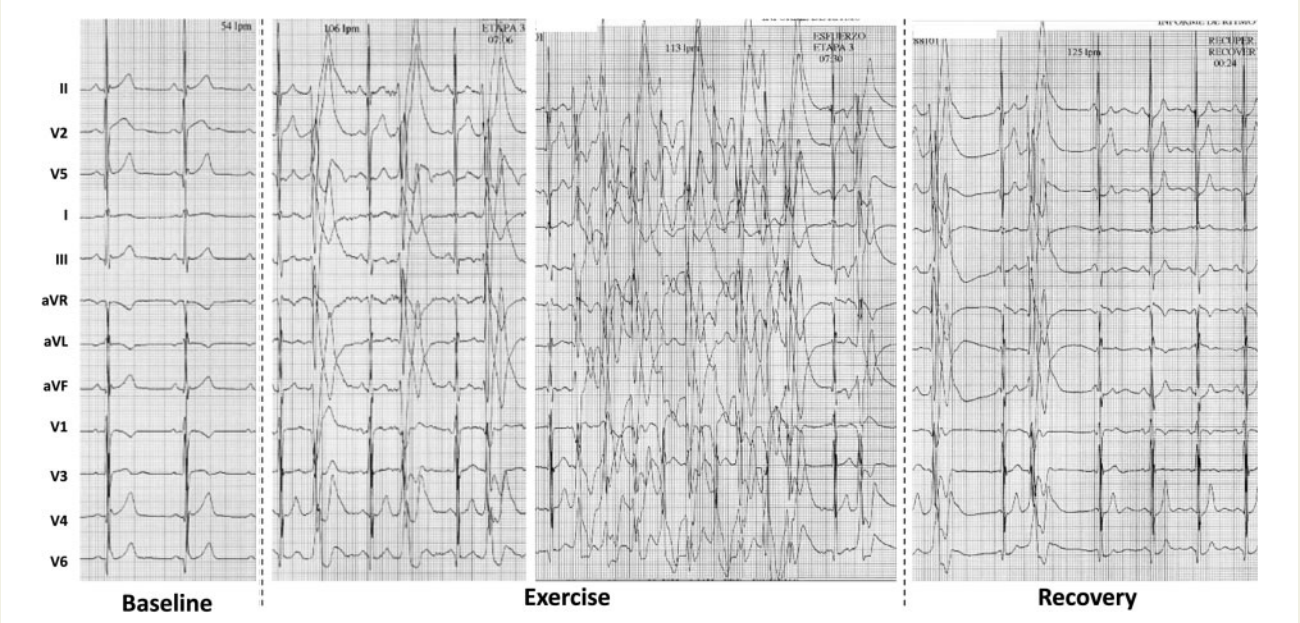

Figure 5 Stress test in a patient with catecholaminergic polymorphic ventricular tachycardia. At baseline, there is normal sinus rhythm with no ventricular ectopy. During exercise, as the heart rate increases there are progressively more complex ventricular arrhythmias. During early recovery, the ventricular ectopic activity ceases.

untreated, up to 60% of patients will have experienced syncope and 30% SCD by the age of 40.[44,187]

Catecholaminergic ventricular tachycardia patients have a normal resting ECG and no structural anomalies; therefore, the disease can only be detected if the athlete undergoes exercise testing. Diagnosis is made when catecholamine-induced bidirectional or polymorphic VT is observed in individuals <40 years of age.[163] Family members with a pathogenic mutation or showing complex premature

Consensus statement—catecholaminergic polymorphic ventricular tachycardia	Symbol
In CPVT patients, competitive and intensive leisure-time sports are NOT recommended.	
Under appropriate treatment, if stress-test shows absence of any type of ventricular ectopy/arrhythmia and if the patient is asymptomatic for a minimum of 3 months, low-intensity to moderate leisure-time sports may be considered, including those with an ICD.[a]	
Gene carriers of a pathogenic CPVT mutation without an overt phenotype should be managed as patients with manifest CPVT (i.e. only allowing low-intensity sports). A beta-blocker should be considered.	
Follow-up should include stress tests and/or continuous ECG monitoring (Holter) during leisure-time low-intensity sports activities to ensure control of exercise-induced ventricular arrhythmias.	
Avoidance of stressful/emotional situations, dehydration, electrolyte disturbances, or hyperthermia is recommended.	

[a]Avoid contact sports in case of ICD implanted.

ventricular contractions or bidirectional/polymorphic VT induced by exercise are also considered to have CPVT.[163] The presence of a positive family history of SCD <40 years and the presence of exercise-induced ventricular ectopy should raise suspicion.[163]

Long-term management strategies in CPVT have the objective of reducing adrenergic stimulation. Lifestyle modifications include avoiding emotional stress and restricting sports activity not exceeding current recommendations for the general population (i.e. moderate intensity physical activity of 30–60 min/day on 3–7 days per week).[62,174,188] Ventricular arrhythmias may also occur at intermediate heart rates (100–130 b.p.m.) during moderate intensity activity, such as playing at school or in recreational sports. However, preliminary retrospective analyses suggest that, with appropriate treatment, sport practice may be possible when avoiding sudden bursts of exercise.[189] Therefore, intensive or strenuous but not moderate physical exercise is discouraged unless exercise testing or Holter recording has demonstrated persistent arrhythmias despite treatment during moderate activity.[62] Based on prior exercise testing, individualized maximal heart rate limits may be specified.

Initial medical therapy includes beta-blocker treatment without intrinsic sympathomimetic activity.[62,174,188] Flecainide, which is a direct RYR2-channel blocker, can be used in association with beta-blockers in case of recurrence despite standard therapy.[62,174,186,188,190–194] Left cardiac sympathetic denervation is an alternative in patients who are not appropriately controlled with medical therapy.[62,186,193] Finally, ICD implantation is recommended for patients who remain symptomatic despite treatment (pharmacological with/without sympathetic cardiac denervation) or who have experienced an aborted SCD.[62,186] In CPVT patients with an ICD, the high risk of an arrhythmic storm is particularly high.[195]

Arrhythmogenic cardiomyopathy

Arrhythmogenic cardiomyopathy is a heritable cardiac disorder histologically characterized by fibrofatty replacement of the right and/or left ventricular myocardium.[196] Clinically, it is characterized by life-threatening VAs and high risk of SCD which are often triggered by exercise or adrenergic stress.[197,198] Although its prevalence is relatively low (1 out of 2500–5000),[196,199] it is an important cause of SCD in young individuals and athletes.[197,199]

Its diagnosis is based on the 2010 Task Force Criteria,[23] which combine electrophysiological and anatomical features with genetic testing and clinical features of the disease. The genetic testing reveals mutations in ~50% of patients, and the most common mutated genes encode cardiac desmosome proteins.[200] In some families, mutations in the ryanodine–receptor gene have been detected, indicating that there may be overlap forms between AC and catecholaminergic VT.[201] ECG is a central element of the diagnosis: it is abnormal in most athletes, and electrical abnormalities usually precede structural changes.[196] Common ECG changes include repolarization abnormalities (inverted T waves), conduction and depolarization disturbances.[202] In advanced stages of the disease, 2D echocardiography and CMR may exhibit a dilated right ventricular (RV) cavity and RV motion abnormalities. However, in early stages and also in the left-dominant variant, morphological AC-related changes may be mild and undetectable by standard 2D echocardiography. Cardiac magnetic resonance and echocardiographic deformation imaging provide a precise evaluation of motion abnormalities,[203,204] and CMR gives information on tissue characterization facilitating AC diagnosis in these early stages.[205]

Arrhythmogenic cardiomyopathy is characterized by reduced penetrance and variable expressivity making risk stratification even more essential.[196] Established risk factors for life-threating VAs include: prior aborted SCD, unexplained syncope, sustained ventricular tachycardia, and right and/or left ventricular dysfunction.[206] Exercise has also emerged as a consistent risk factor for accelerating the disease phenotype and promoting fatal arrhythmias.[69,207] In murine models of desmosomal cardiac mutations, high-intense exercise accelerated disease development,[208,209] arrhythmic presentation,[210] and AC morphological changes. Similar results have been confirmed in genotype-positive phenotype-negative AC patients in which high-intense exercise was related with an increased penetrance,[69,211] an increased risk for ventricular tachyarrythmias,[69] an accelerated myocardial dysfunction and heart failure development.[69,211] Additionally, exercise load reduction resulted in lower VAs burden,[69] and restricting exercise to the AHA minimum

Consensus statement—AC	Symbol
Individuals diagnosed with definite or borderline AC[a] should not participate in competitive sports and should avoid leisure-time activities of moderate to high intensity.	
Individuals diagnosed with possible AC[a] based on one major criterium should not participate in competitive sports and should avoid leisure-time activities of moderate to high intensity.	
In individuals diagnosed with possible AC[a] based on two minor criteria, sports eligibility should be considered on an individual basis after a comprehensive evaluation of the potential diagnosis. Specifically, for the following combination of minor criteria, intensive, and competitive exercise restriction is reasonable: • Family history and any additional minor criterium from a different category. • Tissue characterization and any additional minor criteria from a different category.	
The recommendations to avoid leisure-time activities of moderate to high intensity apply also for genotype-positive phenotype-negative individuals and gene-elusive AC patients.	
The need for ICD should be evaluated based on risk stratification criteria and not for the sole purpose of continuing athletic activity.	

[a]Diagnostic terminology for current Task Force criteria[23]:
- definite diagnosis: two major, or one major and two minor criteria, or four minor criteria from different categories;
- borderline: one major and one minor, or three minor criteria from different categories;
- possible: one major, or two minor criteria from different categories.

Consensus statement—dilated cardiomyopathy	Symbol
The presence of LV cavity dilatation with preserved LV function, in the absence of a family history of DCM, abnormal ECG patterns, and atrial/ventricular tachyarrhythmias should be considered to represent expression of physiological cardiac remodelling rather than DCM. Therefore, no restriction to competitive sports is applicable to this cohort of athletes.	
It seems reasonable that athletes with an unequivocal diagnosis of DCM, but mildly reduced LV systolic function (EF ≥40%) may selectively be allowed to participate in all competitive sports (with the exception of those in whom occurrence of syncope may be associated with serious harm or death), provided that they are: (1) asymptomatic, (2) without prior history of unexplained syncope, and (3) without frequent/complex ventricular tachyarrhythmias on ambulatory ECG monitoring and exercise testing.	
Athletes with a diagnosis of DCM who are: (1) symptomatic, or have (2) LV ejection fraction <40%, or (3) extensive LGE (i.e. >20%) on CMR and/or (4) frequent/complex ventricular tachyarrhythmias on ambulatory ECG monitoring and exercise testing, or (5) history of unexplained syncope. should be advised not to engage in competitive sports. These patients should be advised to limit their exercise programmes to leisure-time activities and undergo regular clinical surveillance, consistent with current recommendations for the management of DCM.	

Adapted from Ref.[2]

upper bound (i.e. </=650 MET h/year) substantially reduced the expression of disease phenotype.[207] Among athletes with definite AC diagnosis, participating in competitive sports was associated with premature disease presentation,[205] and an increased risk of ventricular tachyarrhythmias and SCD.[212] Furthermore, exercise load (intensity + duration) demonstrated to be the best predictor of ventricular dysfunction while exercise intensity alone was an independent predictor of VAs.[213] Similar to AC mutations carriers, the reduction of exercise load in AC patients decreased the risk of VAs and SCD.[214] On the other hand, there is also emerging evidence of an athlete's cohort that fulfilled AC criteria but in which no known AC mutations could been found ('gene-elusive AC' or 'exercise-induced AC' patients), suggesting that intense exercise alone can result in disease development.[43,215,216]

All these data support a restrictive approach regarding sports competition and high intensity exercise training in athletes with positive genotype and/or positive phenotype for AC, but they support low intensity exercise training for a healthy lifestyle. AC athletes should be informed about the current evidence of the whole spectrum AC exercise-related risks in the context of their particular case. Given that AC usually affects young adults and that it demonstrates high risk of SCD, a main clinical decision in AC patients is the placement of an implantable cardioverter-defibrillator (ICD).[217] This decision should be made based on current risk stratification criteria and not for the sole intention of maintaining athletic activity.[218]

Dilated cardiomyopathy

Dilated cardiomyopathy (DCM) is a primary myocardial disease characterized by a dilated and hypokinetic left ventricle with or without associated right ventricular dysfunction. Supraventricular and VAs are present in almost 40% of cases.[219] Although infrequent, DCM is a recognized cause of SCD in athletes. In addition, the physiological response to endurance exercise may result in an enlarged LV cavity with mildly reduced systolic function, causing diagnostic confusion with a mild form of DCM.[220]

Evaluation of athletes with a suspected or confirmed diagnosis of DCM should include a baseline 12-lead ECG, a transthoracic echocardiogram, a cardiopulmonary exercise test, and an ECG monitor which should include monitoring during training or competition. Additional investigations may be required for diagnosis and risk stratification including cardiovascular MRI, exercise imaging studies, genetic testing, familial evaluation, and repeat assessment after a period of detraining.

For detailed exercise recommendations for athletes with DCM we refer to the recently published document by the Sport Cardiology Section of the European Association of Preventive Cardiology (EAPC).[2] The document allows for a more individualized approach where well-informed athletes, with a low-risk profile (asymptomatic status, EF ≥40%, absence of frequent, complex, or exercise-induced arrhythmias) may participate in all competitive sports, depending on existing medicolegal practices. Annual follow-up is recommended but may be more frequent (6 monthly) in adolescent and young adult athletes who are more vulnerable to exercise-related SCD.

Athletes with a pathogenic variant capable of causing DCM but who do not have phenotypic evidence of DCM after comprehensive evaluation, should be allowed to compete in all sports but remain under periodic surveillance to monitor the potential progression to a DCM phenotype.

Hypertrophic cardiomyopathy

Hypertrophic cardiomyopathy is an inherited myocardial disease characterized by a hypertrophied left ventricle in the absence of cardiac or systemic disease capable of inducing the same magnitude of

left ventricular (LV) hypertrophy.[221] Its prevalence in the general population is estimated at 1 in 500 individuals and it has consistently been implicated in exercise-related SCD.[197,222] The majority of athletes with HCM are asymptomatic and are identified following the investigation of an abnormal ECG. Occasionally, athletes are evaluated as a result of familial disease or symptoms.

Evaluation of athletes is similar as described above for DCM.

Detailed exercise recommendations on athletes with HCM have been published by the Sport Cardiology Section of the European Association of Preventive Cardiology (EAPC).[2] The document allows for a more individualized approach where well-informed athletes, with low-risk profile (asymptomatic status, absence of frequent, complex or exercise-induced arrhythmias, no significant left ventricular outflow gradient at rest or on exercise, low 5-year ESC risk score), may be able to participate in all competitive sports, depending on existing medicolegal practices. Annual follow-up is recommended but may be more frequent (6 monthly) in adolescent and young adult athletes who are more vulnerable to exercise-related SCD.

Available evidence from relatively small studies suggests that gene carriers for HCM do not incur excess risk.[223,224] Athletes without phenotypic evidence of the disease after comprehensive evaluation, should be allowed to compete in all sports but remain under periodic surveillance to monitor the potential development of an overt HCM phenotype.

Consensus statement—HCM	Symbol
Participation in intensive exercise programmes and competitive sport should be considered on an individual basis, after full evaluation of the disease characteristics and risk determinants, and with agreement between the athlete and the physician.	
It seems reasonable that adult athletes may selectively be allowed to participate in all competitive sports (with exception of those where occurrence of syncope may be associated with harm or death) if: (1) Mild clinical expressions of HCM (2) Low ESC risk score[221] (3) Adult age Such athletes should be reviewed annually to assess symptoms and changes in risk profile.	
Conditions that reasonably represent absolute contraindications for sport participation include: (1) history of aborted SCD/CA; (2) symptoms, particularly unheralded syncope; (3) exercise-induced ventricular tachycardia; (4) high ESC 5-year risk score[221]; (5) Significant increase in LV outflow gradient (>50 mmHg); and (6) abnormal blood pressure response to exercise (<25 mmHg systolic pressure increase during exercise).[225]	

Adapted from Ref.[2]

Familial disease of unknown origin

A familial pattern of clinical events may be present without structural heart disease or electrocardiographic patterns that fall under a defined condition. Clinical events may include documented arrhythmias, unexplained presyncope or syncope, and sudden death. In some cases, monitoring family members over time may uncover a clear phenotype. In others, pooling of clinical and genetic data, may result in the discovery of novel conditions. Three recent representative examples include: (i) the 'early repolarisation syndrome', where the presence of J-point elevation ≥1 mm in ≥2 contiguous inferior and/or lateral leads of a 12-lead ECG has been associated with increased risk of malignant arrhythmias.[226] Early repolarization, however, is frequently present on the ECG of athletes and outside the context of symptoms or concerning family history is considered a normal variant.[227] (ii) 'multifocal ectopic Purkinje-related premature contractions (MEPPC)' is characterized by atrial and VAs and conduction defects which may progress to dilated cardiomyopathy.[228] The condition has been attributed to pathogenic variants in the SCN5A gene and may specifically benefit from Class-1 antiarrhythmic drugs or amiodarone; (iii) 'familial cardiac arrhythmia syndrome with widespread ST-segment depression' is an autosomal dominant cardiac syndrome characterized by marked, persistent, non-ischaemic ST-segment depression, the development of atrial fibrillation and VAs, and some degree of left ventricular dysfunction.[229] The genetics of this condition remain elusive. It is likely that the future will reveal more familial arrhythmogenic disorders, of which some can create particular vulnerability during exercise.

Consensus statement—familial disease of unknown origin	Symbol
Athletes with antecedents of undefined familial history of arrhythmias and/or SCD, require referral to an expert cardiogenetics centre, since rare forms of inherited familial syndromes are being described.	
In the absence of definitive risk stratification algorithms, exercise recommendations in these athletes should be governed by symptoms, family history, frequency and complexity of arrhythmias, and the presence of a concomitant cardiomyopathy.	

Device therapy

Pacemakers and resynchronization therapy

Although there are no available data, pacemaker (PM) carriers are rare among those who practice sports. Recommendations are important for (i) those practicing regular sports activity but who are in

need of a PM and want to know if they can continue after implantation, and (ii) for PM patients with an underlying heart disease (ischaemic cardiomyopathy, heart failure) in whom rehabilitation and regular sport practice are considered important to improve outcome.[230] Usually, PM patients have less severe disease and comorbidities than implantable defibrillator (ICD) carriers. Moreover, there is less risk of malfunction for a PM than for an ICD.[231] For all these reasons, it seems that one could be more permissive for sports practice in patients with a PM.

In the absence of structural heart disease, competitive or recreational sports participation is allowed. In patients with a PM and underlying heart disease, recommendations to these underlying diseases apply. E.g. in patients implanted with a cardiac resynchronization device for heart failure treatment (CRT), mild to moderate sport practice is beneficial and possible.[232]

For all implanted patients (PM, CRT, and ICD), sport activities with a risk of chest trauma or violent contacts (e.g. rugby, boxing, martial arts) should be avoided.[233–236] Other sports (like soccer, basketball, baseball) can be allowed while wearing appropriate padding. In addition, sports with pronounced arm movements (like volleyball, basketball, tennis, climbing) may also increase the risk for late lead damage due to subclavian crush (with insulation or conductor failure).[234,237,238] Because there is no concern on lead fracture, leadless pacemakers could be potentially more adapted for some sports or athletes.

Precautionary implantation measures, like the use of bipolar leads,[239] implantation on the contralateral side of the dominant arm (e.g. at the left side in a right handed tennis player), extrathoracic access of the subclavian vein,[240] fixation within the pocket or submuscular placement, and avoidance of full arm movements until complete healing and fixation of the leads (at least 4 weeks) should be particularly considered in these patients.

After implantation, individual programming of the upper sensor and the tracking rate guided by exercise testing and/or Holter ECG (and excluding inappropriate rate acceleration in other circumstances, e.g. horse-back riding)[241] is required. Follow-up should be regularly scheduled (usually every 6 months, or telemonitoring with regular transmissions).

Electromagnetic interference is unlikely with modern devices and no cases have been reported, but should always be suspected and closely evaluated in specific athletic environments with electronic equipment. Also, myopotential sensing may result in inhibition of pacing, a problem that is more common with unipolar electrodes, although it usually can be corrected with appropriate reprogramming of the device.[239,242] Bipolar leads are less sensitive to this problem.

Consensus statement—pacemakers and resynchronization therapy	Symbol
Athletes with pacemakers with/without resynchronization and underlying disease need to follow the recommendations pertaining to the underlying disease.	
Without evidence for structural heart disease or inherited arrhythmogenic condition, all sports are allowed.	
Direct impact to the device should be prevented by adapting the site of lead and/or device implantation, by padding or restricting direct impact sports.	
Holter recordings and device interrogation allow appropriate tailoring of rate-responsive pacing parameters, exclusion of myopotential or electromagnetic inhibition, and detection of VAs.	
A 6 monthly follow-up or remote monitoring should be instituted in pacemaker carriers with moderate to intense sports participation.	

Implantable cardioverter-defibrillators

Although receiving an ICD *per se* does not necessarily impair overall quality of life,[243] ICD recipients do perceive restrictions for physical activity after ICD implantation as limiting, and express fear for receiving shocks.[244] Staying active is important for its proven benefits, both mentally and physically,[245] also in ICD patients.[246] In this context, physical exercise should be encouraged.

Previous recommendations concerning sports participation in ICD recipients were restrictive,[6,8] primarily based on theoretical considerations, due to the lack of scientific data.[247]

Recently, follow-up data on 440 athletes in the Sports ICD Safety Registry (393 participating in organized competitive sports, 47 in high-risk sports) have been reported.[199,248] Also the outcomes of 80 additional recreational athletes are available.[249] These data are important as they can serve to counsel competitive and leisure-time athletes, leading to a process of shared decision-making. Over a median follow-up of 44 months no resuscitated SCD, no significant injury related to arrhythmia or shock and no generator malfunctions occurred. Lead survival was 94% at 5 years and 85% at 10 years.[247,248] Shocks were common: 10% of patients received an appropriate shock during competition or practice. Shocks did occur more frequently during exercise than at rest (20% vs. 10%), but, contrary to common belief, no difference was found between competition/practice and other activities. Recreational athletes, however, experienced fewer appropriate and inappropriate shocks during physical activity than participants in competitive sports.[249] This highlights the issues with the definition of 'sports intensity'. Moreover, of those athletes who received shocks, about 30% stopped sports at least temporarily,[247,249] indicating a psychological impact that may be relevant in the long-term if patients would start to fear therapy from their life-saving device.

In the discussion about whether or not to perform sports with an ICD, we propose attention for 'four Ds' to structure management: danger, disease, device, and dysrhythmias.

Danger

This includes considerations about the safety of the athlete and his/her environment. Conceivably every human has the right to

Consensus statement—ICDs	Symbol
When counselling ICD recipients for sports participation, the underlying disease should be taken into consideration first.	
If not contra-indicated for the underlying heart disease, physical activity should be encouraged in ICD recipients.	
Dangerous situations in the context of loss of focus or consciousness should be avoided, both regarding safety for the athlete as for third parties.	
All athletes with devices should be remotely monitored.	
Shared decision-making should be considered to decide about continuation of intensive or competitive sports participation in ICD patients, taking into account the effect of sports on the underlying substrate, the fact that intensive sports will trigger more appropriate and inappropriate shocks, the psychological impact of shocks on the athlete/patient, and the potential risk for third parties.	
Device implantation and settings should be carefully considered in function of sports participation (e.g. side of implantation, detection times, rate response). Holter recordings and device interrogation allow appropriate tailoring of rate-responsive pacing parameters, exclusion of myopotential or electromagnetic inhibition, and detection of VAs.	
Atrial and VAs need to be treated promptly with low thresholds for ablation to minimize the risk of (inappropriate) therapy	
An ICD is not a substitute for disease-related recommendations when these mandate sports restrictions.	
Implantation of a dual-chamber system for the sole reason of arrhythmia discrimination is not recommended.	

decide on his own life and the risks taken in this context but the safety of others should be respected. This implies that situations where loss of focus or loss of consciousness could cause harm to a third party (like in motor sports, diving, mountain climbing) should be avoided.

Disease

The underlying heart disease plays an important role in the decision about sports participation, where exercise might aggravate the disease or cause or provoke arrhythmias. As such, the disease specific considerations as described above should be taken into account.

Device

Exercise can affect the device in various ways. The same risks for the lead and device and the same implantation related considerations as for pacemakers exist for ICDs (see above). Additionally, the type of device [single chamber, dual chamber, subcutaneous (S-ICD)] must be considered although no firm data in this regard are available in athletes. After implantation, return to sports can be allowed after a 6-week period of (relative) rest, preferably after performing an exercise test. If sport with a high risk of collision is performed, shielding and padding need to be discussed, although its effectiveness has never been proven.

Next, device programming needs attention: the athlete must be aware of the programmed detection rate cut-offs to be able to avoid reaching those during exercise. Conversely, detection zones, tracking- and sensor driven rates, need to be programmed sufficiently high to allow for high (enough) heart rates during exercise. A detection rate cut-off of ≥200 b.p.m. proved safe and reduced the occurrence of shocks in the ICD Sports Safety

Registry.[250] Prior exercise- and long-term ECG recordings will be important for assessment of sinus tachycardia: when inappropriate device triggering due to sinus tachycardia is anticipated, clear instructions to the patient concerning activity limitation and/or institution of bradycardic therapy (with beta-blockers if possible) are mandatory.

Dysrhythmias

Both atrial and VAs need consideration: occurrence of a ventricular tachyarrhythmia can cause both shocks and haemodynamic compromise. This requires an aggressive management with a low threshold for VT ablation. After an ICD intervention or VT ablation, 6 weeks of sports restriction must be respected.

The most common cause of inappropriate shocks in transvenous ICD is the occurrence of sinus tachycardia and supraVAs.[251,252] In several heart diseases (e.g. AC, BS, SQTS)[253] atrial arrhythmias are more prevalent than in control populations. Also, the practice of endurance sports itself carries a higher risk for developing AF.[254,255] As antiarrhythmic drugs potentially interfere with chronotropy and inotropy, ablative therapy should be considered early. Implantation of a dual-chamber ICD for the sole reason of atrial arrhythmia detection and discrimination is generally not warranted since usually not effective.[251,256–259] Given the fact that many of these athletes are young, there is a higher risk for long-term lead complications when more leads are implanted. Therefore, restraint is needed concerning the implantation of more complex ICD systems, and their indication should be weighed in every patient.

Remote monitoring has shown to reduce mortality in the ICD population.[260,261] It also has the potential for early detection of both arrhythmias and device failure. Hence, routine inclusion of athletes in remote monitoring programmes is highly recommended.

In conclusion, athletes with ICDs need to be carefully evaluated and counseled concerning the potential impact of their activity on the ICD and vice versa. A process of shared decision-making, taking into account the underlying heart disease, the athlete's ambitions, the intensity of the exercise and common sense is the fundament of giving a sound advice. Careful follow-up, including remote follow-up, with prompt intervention when novel symptoms or worsening of the underlying heart disease occurs, is mandatory.

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