Is Exercise Helpful or Harmful in Dealing With Specific Arrhythmia

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Abstract: Exercise is universally known to benefit health by lowering risk for cardiovascular disease and mortality. However, in patients with pre-existing cardiac conditions, including channelopathies, cardiomyopathies and coronary artery disease, exercise can cause sudden cardiac death (SCD). In this review, we explore exercise related risks and current recommendations for specific conditions. The risk of myocardial infarction (MI) during strenuous exercise in asymptomatic individuals with coronary artery disease is decreased with habitual exercise, especially if they have a normal ejection fraction and no ischemia. Furthermore, cardiac rehabilitation has been shown to be beneficial in heart failure. On the other hand, surgery is recommended for certain anomalous coronaries prior to engaging in vigorous activity. In addition, both exercise-induced disease progression and SCD in arrhythmogenic cardiomyopathy restrict ability to engage in competitive sports, as is the case in hypertrophic cardiomyopathy. Other diseases, like myocarditis only cause temporary risk for SCD. Previously considered benign, common conditions like early repolarization do increase SCD risk. Finally, certain gear including thicker chest protectors for athletes engaging in sports with hard, small spherical objects decrease risk of commotio cordis. While significant advances have been achieved in diagnosing and treating previously unrecognized

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conditions that predispose to sudden cardiac death, more research is needed to further tailor recommendations to allow beneficial exercise in those with rarer conditions that are under-represented in large systemic studies. (Curr Probl Cardiol 2021;46:100740.)

Introduction

The health benefits of exercise have been readily described in literature.[1] In fact, studies have consistently demonstrated the reduction of cardiovascular (CV) and all-cause mortality in those engaging in regular exercise.[2,3] Physically, active individuals have 35% less risk of CV death over 20 years as compared to their inactive counterparts.[4] However, despite the plethora of health-promoting evidence, exercise can paradoxically increase the risk of sudden cardiac death (SCD) in those with pre-existing cardiac abnormalities, accounting for 1 in 40,000 to 1 in 80,000 athlete deaths per year.[5] Sudden cardiac arrest, commonly defined as the termination of mechanical cardiac function within an hour of symptom-onset, can be due to either a congenital or acquired cardiac abnormality.[6-8] Ventricular tachyarrhythmias are the most common arrhythmia associated with SCD[9] and result from the combination of both a substrate and trigger. Substrates such as myocardial scarring due to ischemia or conduction system abnormalities can be lethal in the setting of triggers like exercise-induced stress.[10]

Age is an especially important factor for risk stratification in exercise-related SCD. Inherited cardiac channelopathies and cardiomyopathies account for the majority of SCD in younger athletes ($\leq$35 years of age)[11-13] while acquired diseases such as coronary atherosclerosis or congestive heart failure account for most SCD in older athletes (>35 years of age)[14-16] (see Table 1). While some cardiac abnormalities present with more easily identifiable characteristics, SCD may be the first manifestation in others. For this reason, early identification is of paramount importance to reduce the risk of SCD in susceptible individuals.

The American College of Cardiology defines an athlete as any person engaging in routine exercise whether competitive, recreational or occupational.[17] However, not all sports are equal in myocardial demand and hemodynamic stress. Thus, the type of athlete and rigor of their sport are essential components in determining whether exercise should be prescribed or restricted. Levine et al classified sports based on both static (numbers I, II, and III) and dynamic (letters A, B, and C) intensity components.[18] Highly static exercises (III) increase the pressure load on the

Table 1. Most common structural abnormalities and channelopathies that cause sudden cardiac death.

Cardiac causes of SCD		
Structural		**Channelopathies**
≤35 Years	**>35 Years**	Brugada syndrome
Hypertrophic cardiomyopathy	Atherosclerotic coronary disease	Congenital Long QT syndrome
Anomalous aortic origin of coronary artery	Congestive heart failure	Catecholaminergic polymorphic ventricular tachycardia
Arrhythmogenic cardiomyopathy		Short QT syndrome
Myocarditis		Early Repolarization syndrome
Isolated LV noncompaction		

left ventricle while highly dynamic sports (C) increase the volume load. Therefore, athletes with cardiac abnormalities which cannot endure highly dynamic loads are restricted from IC, IIC, and IIIC sports.

In this review article, we will discuss the most relevant structural abnormalities and channelopathies, mechanisms of SCD, and the current recommendations for either exercise restriction or prescription for each subgroup.

Structural Abnormalities

Patients with pre-existing cardiac structural abnormalities comprise a large proportion of those who experience sudden cardiac death.[10] The most common arrhythmias associated with cardiac arrest are ventricular tachyarrhythmias.[9]. These usually occur in the setting of both a trigger such as hemodynamic fluctuation and a substrate like myocardial scarring.[6,9] During exercise, the catecholamine surge may serve as a potential trigger to initiate the fatal electrical cascade in the setting of a congenital or acquired arrhythmogenic substrate.[19] Age is one of the most important factors in risk stratification of SCD during exercise, because older patients (age ≥35 years) are more likely to suffer from acquired diseases such as atherosclerotic coronary artery disease (CAD)[15,20] while younger patients (age <35 years) are likely more afflicted by congenital cardiac abnormalities.[21] In this section, we discuss the relationship of some notable structural cardiac abnormalities and the impact of exercise on the respective patient populations.

Atherosclerotic Coronary Disease

The most common cause of SCD during exercise in athletes >35 years of age is atherosclerotic CAD.[11,15,22] Marijon et al demonstrated CAD as

the source of sports-related SCD in 84% of athletes.[23] Autopsies of marathon runners following SCD have shed light on the possible mechanisms of cardiac instability during exercise. Specifically, these include: ventricular arrhythmias originating from prior myocardial scarring, acute ischemia induced by plaque rupture, or demand ischemia from advanced coronary stenosis.[14,24,25]

While the health benefits of physical activity have been clearly demonstrated,[1] the overall relative risk of myocardial infarction (MI) is shown to be higher during exercise as compared to rest.[26] This "exercise paradox" is secondary to the transient elevation in risk of fatal arrhythmia or ischemia during strenuous exercise.[26] Importantly, however, the risk during exercise is decreased, and perhaps insignificant, in those who participate in habitual exercise as compared to those who do not.[14,27] In fact, regular exercise in most individuals with coronary disease and history of MI decreases deleterious cardiac remodeling overtime[28]; exercise-based cardiac rehabilitation following an acute CV event is a vital component of secondary prevention and has been shown to effectively decrease cardio vascular mortality, all-cause mortality and improve quality of life.[29] With the number of endurance athletes and diagnosis of subclinical CAD increasing,[16] appropriate exercise prescription or restriction parallels in importance.

Currently, AHA/the American College of Cardiology guidelines recommend that athletes with underlying CAD undergo left ventricular function and exercise testing to evaluate for evidence of inducible ischemia and maximal exertional tolerance (Class I, Level of Evidence C).[30] In general, it is reasonable for athletes with CAD who have no evidence of inducible ischemia, who remain asymptomatic, and have a resting left ventricular ejection fraction more than 50% to participate without restriction in competitive sporting activities (Class IIb, Level of Evidence C).[30] The European Association of Preventive Cardiology considers athletes at low-probability for exercise-related cardiac events if all criteria are met: left ventricular ejection fraction $\geq$50%, no inducible ischemia or ventricular tachycardia with exercise testing, absence of significant coronary stenosis on angiography (<70% major coronary vessels or <50% of left main stem), and age-appropriate exercise tolerance.[31] Failure to meet any one of the previous criteria prompts temporary exercise restriction from competitive sports until treatment is achieved.[31] Ultimately, not all athletes with atherosclerotic CAD possess the same risk; shared decision-making and personalization play a significant role in making exercise prescription or restriction for patients.

Heart Failure

With the prevalence of heart failure (HF) at 1%-2% in developed countries,[32] it is responsible for approximately one million hospitalizations per year in the United States.[33] The 2 main subgroups of HF, heart failure with reduced ejection fraction (HFrEF) and heart failure with preserved ejection fraction (HFpEF), have different etiologic and arrhythmogenic properties. HFrEF patients have declining LV systolic function marked by cardiac dilatation and scarring which can breed ventricular tachyarrhythmias independent of coronary ischemia.[34,35] Approximately 40% of deaths in this population are due to SCD secondary to ventricular arrhythmias.[36] On the other hand, HFpEF patients who have impairment of diastolic function with left ventricular hypertrophy (LVH) and increased myocardial fibrosis, can provide an underlying substrate for sustained ventricular arrhythmias.[37] In fact, concentric LVH has been shown to be an independent risk factor for SCD.[38]

Prior to 1980, exercise restriction and bedrest were recommended for patients with HF.[39] Sullivan et al first demonstrated improvement of exercise tolerance in ambulatory HF patients[40]; later, exercise was shown to safely improve physical capacity and HF symptoms[41] thereby eradicating the belief of bedrest for cardiac preservation in HF. Reduced exercise tolerance is an independent risk factor for hospitalizations and mortality for HF patients.[42]

In patients with established HF, exercise training plays an adjunct role in their management and treatment strategy. HF-ACTION, a randomized, controlled trial including 2331 medically stable patients with HFrEF, demonstrated improved cardiorespiratory fitness, reduced HF hospitalizations, and improvement in quality of life in patients who underwent moderate-intensity aerobic training up to 3 times per week.[43] Additionally, Haykowski et al found improved left ventricular (LV) remodeling, specifically decreased LV end-diastolic diameter and improved ejection fraction, in HF patients who underwent aerobic exercise training.[44] Smaller randomized controlled trials have demonstrated high-intensity interval training to more effectively improve cardiorespiratory fitness than moderate intensity training in both HFrEF and HFpEF.[45] For these reasons, ACC/AHA recommends exercise training to safely and effectively improve functional status in all stable outpatient HF patients in conjunction with drug therapy (Class I, Level of Evidence A). Cardiac rehabilitation has also been shown to reduce mortality and hospitalizations (Class IIa, Level of Evidence B).[46,47] The main cardiac contraindications for exercise in HF include acute decompensated disease, NYHA functional

class IV, and coexistent severe valvular dysfunction.[48] Overall, while current guidelines do not necessarily specify the intensity or dose of physical activity for HF patients, exercise plays a significant role in the management of HF and should be considered safe and effective in those with chronic, stable HF.

Hypertrophic Cardiomyopathy

Hypertrophic Cardiomyopathy, estimated to have a prevalence of 1 in 200 adults,[49] is an autosomal dominant cardiac disorder of sarcomere and myo-filament proteins which manifests as increased LV wall thickness ($\geq$15 mm) not attributable to other causes of hypertrophy.[50] This results in diastolic dysfunction and is also associated with other LV structural changes including hyperdynamic contraction, smaller LV cavity size, and LV outflow tract obstruction.[50,51] EKG findings in HCM are nonspecific and primarily reflect LVH with findings such as T-wave inversions, prominent precordial voltages, left axis deviation and inferior and/or lateral Q waves suggestive of hypertrophied septal depolarization.[52] Notably, 5%-10% of those with echocardiographic evidence of HCM have normal ECGs.[53] HCM is a heterogenous disorder with wide phenotypic variability ranging from asymptomatic patients to progressive heart failure or SCD.[54] The mechanism of HCM-related SCD is based in the downstream effects of myocardial hypertrophy, microvascular ischemia and resultant apoptosis. Subsequent fibrous substitution and disarray of the myocardium ultimately serves as a hotbed for ventricular tachyarrhythmias in the presence of the high-adrenergic state of exercise.[10,55-57]

With HCM being the leading cause of SCD in US athletes[12,58] and accounting for nearly 40% of SCD in young athletes,[12] it has a profound psychological impact on patients leading to adopting sedentary lifestyles with its downstream physical and psychological sequalae.[59-61] Ultimately, the aim of professional recommendations is to mitigate the risk of HCM complications, particularly SCD. The risk of HCM-related SCD is highest in those $<$30 years of age but decreases notably in those $>$60 years of age[62]; the presence of major factors such as family history of SCD, syncope, LVH $\geq$30 mm, LV apical aneurysm or reduced EF $<$50% confers the highest risk for SCD.[63] International recommendations have staunchly excluded HCM athletes from the majority of competitive sports with possible exception of low-intensity sports[64,65] as classified by Levine et al.[18] While the European Society of Cardiology similarly recommends that high risk patients not participate in competitive sports, it has most recently suggested a more personalized approach for low-risk,

adult patients to be selectively evaluated for competitive and recreational athletics.[66] Small-scale studies have shown that moderate-intensity exercise programs in HCM patients safely improve heart rate recovery, functional capacity, and exercise capacity without evidence of phenotype progression or adverse outcomes.[67,68] Overall, consensus guidelines on exercise in HCM traditionally support a restrictive approach to mitigate the risk of SCD, but emerging data on safety of exercise in this population is introducing, perhaps, an individualized approach for patients.

Anomalous Aortic Origin of Coronary Artery

Anomalous aortic origin of coronary arteries, while rare, are the second leading cause of SCD in patients <35 years of age, accounting for about 17% of SCDs in U.S. athletes.[12] Prevalence ranges from the most common subtype, anomalous RCA, at 0.9% to the least common, anomalous left coronary artery (LCA), at 0.02%.[69-71] Clinically, the presentation of these patients varies from asymptomatic to SCD[69,72,73] which is an immense challenge from a SCD prevention standpoint as both ECG and stress test are not reliable screening tools.[74] Additionally, while some patients have syncope or exertional angina, approximately 50% of SCDs attributable to anomalous origin of coronary arteries present as first events without previous symptoms.[75] Ultimately, when the disease is suspected, the ideal technique for definitive diagnosis includes computed tomography angiography, magnetic resonance angiography or coronary angiography.[76]

While involvement of all 3 main coronary arteries is possible,[77] anomalous aortic origin by the left coronary artery from the opposite sinus of Valsalva is the most associated with SCD of athletes.[12,75] Anatomically, the artery has an acute angle takeoff from the aorta but may have intramural segments and/or an interarterial course whereby the lumen of the artery is slit-like or compressed between the aorta and pulmonary artery.[78] Consequentially, the artery is unable to meet the increased myocardial oxygen demand during exercise and ischemia ensues. Over time, repetitive ischemic injury results in fibrous repair and resultant substrate formation for fatal ventricular tachyarrhythmias.[79] The presence of intramural or interarterial segments are believed to confer the highest risk for SCD.[70,80]

AHA/ACC recommendations[76,81] for management of anomalous aortic origin of coronary artery is primarily surgical, especially for anomalous LCA from the right sinus. Patients with an anomalous LCA from the right sinus should be restricted from all competitive sports, with possible exception of class IA sports, while awaiting surgical repair (Class III,

Level of Evidence B).[76,81] After that time, at least 3 months following surgical repair is required before individualized consideration of any participation in sports for the athlete. On the other hand, management of patients with anomalous RCA from left sinus can be based on the presence of symptoms or a positive stress test. If diagnostic evidence or symptoms of ischemia is present, surgical repair is recommended. However, asymptomatic patients without a positive stress test should undergo adequate counseling regarding the risk and benefit before considering permission to compete in sports, especially knowing the poor screening ability of the stress test.[76,81]

Arrhythmogenic Cardiomyopathy

Arrhythmogenic cardiomyopathy (ACM), formerly described mainly as arrhythmogenic right ventricular cardiomyopathy (ARVC), is a rare, autosomal dominant cardiomyopathy[82] characterized by progressive myocyte loss with fibrofatty replacement of the myocardium primarily due to cell-to-cell adhesion protein mutations, particularly desmosomes.[83] While the disease was initially believed to only affect the RV, subsequent autopsies along with the advent of CMR have revealed LV involvement and origin of the disease, leading to evolution of the term.[84,85] ACM is rarely diagnosed prior to 12 years of age with a mean diagnosis age of 30 years.[86] With an overall prevalence of 1:5000 and higher in Europe,[87] this disease is the most common cause of SCD in athletes of Italy and Denmark age <35 years of age, accounting for approximately 25% of cases.[88,89] While less common in the U.S., claiming <5% of SCDs in athletes,[12] its distinguishable association with both exercise-induced disease progression and SCD makes it a critical area of advice for inflicted athletes.[90]

The ECG can sometimes be helpful for screening athletes with ACM. In fact, RV dominant phenotypes can manifest with changes in the right precordial leads: QRS duration >110ms in V_1, epsilon wave in V_1 and V_2, and T-wave inversions in V_1 to V_3.[91] Moreover, ventricular arrhythmias such as PVCs or sustained ventricular tachycardia with a left bundle branch block-like morphology in V_1 suggests RV electrical origin.[92] On the other hand, ventricular arrhythmias having a right bundle branch block-like morphology signifies LV origin.[85] However, diagnosis of the disease is multifaceted and incorporates findings by electrophysiology, imaging, family history, and histology.[92]

The interaction between exercise and ACM is 2-fold as exertion increases both the acute risk of SCD and the progressive deterioration of

the ventricle. Firstly, the fundamental mechanism of SCD in inflicted patients is based in the fibrofatty myocardial infiltration serving as a substrate for re-entry of ventricular tachyarrhythmias.[87] James et al demonstrated that patients who underwent the most exercise suffer the highest burden of ventricular tachyarrhythmias. Furthermore, reduction in exercise of those patients decreased the risk of VT/VF from 75% to 12%.[90] Secondly, exercise-related progression of ACM results from repeated myocyte detachment and death due to impaired adhesion of cells in the setting of elevated ventricular wall stress during exercise.[83] Studies in carriers of ARVC mutations revealed earlier development of symptoms in those who underwent endurance exercise as compared to sedentary patients. Additionally, patients who exercise were more likely to develop ventricular arrhythmia and heart failure than their sedentary counterparts.[90,93] For these reasons, exercise restriction from competitive or high-intensity exercise, with possible exception of class Ia sports, is recommended by the Heart Rhythm Society (HRS) guidelines for patients with a diagnosis of ARVC.[94] Additionally, the International Task Force recommends that patients with ARVC not participate in either competitive or endurance sports (Class III, Level of Evidence C).[95] These recommendations have also been extended to patients with established desmosomal mutations but without evidence of phenotypic expression to reduce likelihood of development and SCD.[66,94]

Myocarditis

Myocarditis, an acquired cause of arrhythmias and SCD in young patients, is defined by inflammation of the heart muscle which, in the majority of patients, has a transient and favorable clinical course.[96] Less commonly, serious manifestations of the disease can include acute heart failure and SCD.[97] While definitive diagnosis is based on endomyocardial biopsy, ECG findings typically show diffuse repolarization abnormalities,[98] and echocardiography can show global LV enlargement and dysfunction.[99] 2%-12% of SCD in athletes have been attributed to myocarditis[11,12,100]; in spite of potentially positive effects of moderate intensity exercise on the immune system,[101] high-intensity exercise and persistent overtraining has been shown to decrease the immune system[102] therefore increasing the risk for viral infections that can trigger acute myocarditis.[96] Additionally, Kiel et al. demonstrated increased mortality and myocyte necrosis in mice by exercise during acute myocarditis.[103]

The mechanism of SCD during exercise in patients with myocarditis is most likely explained by the inflammatory cascade due to acute infection

which can result in myocardial edema, necrosis and fibrosis with a resultant proarrhythmic substrate.[104] Additionally, ventricular arrhythmias can occur due to coronary artery spasm secondary to the catecholaminergic surge of acute phase infection.[105] Following resolution of the acute phase, residual myocardial scarring can also pose a threat for fatal arrhythmias in healed athletes.[106]

Current recommendations for patients with probable or definite acute myocarditis include temporary restriction from both competitive and leisure-time exercise.[107] Traditionally, exercise restriction for a minimum of 6 months was recommended,[108] but this has since been reduced to 3 months with possible extension to 6 months depending on disease severity and LV function.[65] Furthermore, full clinical reassessment is recommended prior to resumption of competition including 12-lead EKG, biomarkers, exercise testing, echocardiography and ambulatory ECG monitoring to exclude serious arrhythmias. The potential for myocardial scarring substrate warrants long-term surveillance.[66]

Isolated Left Ventricular Noncompaction

With a prevalence of <0.02%,[109] LV noncompaction is a rare disease defined by its myocardial protrusions and deep intertrabecular recesses which communicate with the LV cavity on a thin, properly compacted myocardial layer.[110] While the true pathogenesis of LVNC is controversial, notable proposed causes include intrauterine arrest of myocardial compaction resulting in pathologically persistent trabeculae[111] or acquired trabeculation as an adaptive physiologic response to LV wall stress causing myocardial remodeling.[112] Signs and symptoms of LVNC are nonspecific and range from dyspnea and syncope to stroke or over heart failure[113]; SCD occurs in 2 to 5% of LVNC cases. Ultimately, diagnosis can be established by CMR or echocardiography using criteria such as Jenni[114] and Chin[115] which have been developed and validated.

The relationship between LVNC and exercise is not fully understood. However, as stated above, trabeculations can be seen in those with either embryogenetic pathology or as a physiologic response to stress such as training. In fact, Gati et al demonstrated that, in over one thousand athletes with excessive trabeculation, only 8.1% met both Jenni and Chin criteria compared to 7% of sedentary controls.[116] With regards to athletes and nonathletes, the presence of LV systolic dysfunction or ventricular tachyarrhythmias are highly associated with increased mortality.[117] Notably, in some patients with LVNC, late gadolinium enhancement of trabeculae has been detected.[118] which could be an attributable substrate for

lethal ventricular arrhythmias in this population, however further studies are needed. Currently, with the limited information available on this disease, AHA guidelines suggest that relatively lower risk for SCD in athletes with LVNC are those with no evidence of systolic dysfunction, tachyarrhythmias on ambulatory monitoring or exercise testing, and no history of unexplained syncope (Class IIb, Level of Evidence C).[65] Any evidence of one of these criteria in a patient with LVNC should prompt restriction from competitive sports, with possible exception of class 1A sports (Class III, Level of Evidence C).[65]

Channelopathies

Individuals with cardiac channelopathies include a small percentage of the population who are genetically affected by abnormal heart rhythms with a structurally normal heart.[119] These cardiac channelopathies included Brugada syndrome, Long-QT syndrome (LQTS), Catecholaminergic polymorphic ventricular tachycardia (CPVT), Short QT syndrome, and Early repolarization syndrome (ERS). The most common cardiac channelopathy is LQTS.[119] The prevalence of cardiac channelopathies as a whole is approximately 1 in 1000, with LQTS estimating 1 in 2000 people.[119] Common symptoms seen in these individuals include syncope, seizures, and possible sudden cardiac arrest.[119] This article will delve more into these individual cardiac channelopathies and the latest guidelines on exercise restrictions for individuals living with these syndromes.

In 2005, Bethesda Conference Guidelines were created for athletes suffering from cardiac channelopathies, with the recommendation to restrict all competitive sports in fear of sudden cardiac death. This recommendation was made regardless of the sport, and regardless of the underlying channelopathy.[64,120] Since then, observational studies have shown that exercise has only been established as a potential trigger for CPVT and LQTS.[121,122] Additional developments have emerged from the HRS and the European Heart Rhythm Association in 2011.[123] The first being the clinical importance of genetic testing for cardiac channelopathies. The American Heart Society and the ACC published a list of recommendations for eligibility and disqualification for competitive athletes with cardiac channelopathies in 2015.[124] They reiterate the 2011 HRS/the European Heart Rhythm Association recommendation that individuals suspected or diagnosed with cardiac channelopathy need to be evaluated by either a heart rhythm specialist or genetic cardiologist. Once an athlete with or suspected cardiac channelopathy complains of symptoms, further involvement in competitive sports need to be stopped until a work-up by

the specialist above has been completed.[124] A treatment plan must be identified, understanding from the patient and his family of this treatment plan, and the patient must be asymptomatic on this therapy for at least 3 months.[124] Once asymptomatic, the appropriate precautionary measures must be discussed before returning to sports.[124]

Congenital Long QT Syndrome

Congenital long-QT syndrome (LQTS) is a fatal, genetic disorder caused by mutations in 5 known genes affecting cardiac ion channels.[125] The common types of LQTS are LQT1 and LQT2 from mutations in the KCNQ1 and KCNH2 genes.[125] The LQT1 type is due to a mutation in slow potassium channels, while LQT2 caused by a mutation in the fast potassium channels.[125] LQT1 has been found to be more sensitive to beta-adrenergic stimulation, whether physical or emotional, compared to other congenital long-QT syndrome variants.[122]. When beta-adrenergic stimulation occurs, there is a prolongation of the QT interval due to the upregulation of $I_{Ca,L}$ channels.[125] Different variants of T-wave patterns are also identified for these 2 main types of LQTS. In LQT1, 3 T-wave patterns were identified: broad-based, normal-appearing, and late-onset T waves. In LQT2, there are 2 types of bifid T-waves patterns, with one consisting of a small notch and one with a large notch on the descending T-wave limb.[125] Data from this 2003 Circulation article confirms that the LQT1 variant is more susceptible to prolongation of the QT interval, due to a larger increase in the peak T wave from a transmural dispersion of repolarization from the beta-adrenergic effects of exercising.

Individuals with/suspected LQTS require genetic evaluation. The syndrome affects 1 in 2000 persons. The Mayo clinic has an initial evaluation that takes 2- to 3-days.[126] During this evaluation, ECGs are completed over multiple days, echocardiography, 24-hour ambulatory monitoring, and treadmill exercise testing. Depending on the results of these tests, pharmacological stress testing, consultations to psychiatry, consultation to an ICD implant specialist, genetic counseling, and a surgeon specializing in left cardiac sympathetic denervation are made. Their primary evaluation is usually 1-2 hours in duration. It consists of discussing the diagnosis, prognosis, and therapeutic interventions. Most individuals will return for annual 1-2 day follows for further monitoring.

The AHA and AHC has recommended[7] that athletes can be considered for a return to competitive sports (except LQT1 patients with competitive swimming) after they have been asymptomatic on treatment for at least 3 months and appropriate precautionary measures have been taken, such as

avoiding QT-prolong drugs, preventing electrolyte depletion, avoidance of dehydration, and being mindful of heat exposure.

Brugada Syndrome

The American College of Cardiology has denoted key diagnostic criteria for Brugada syndrome.[127] Brugada Syndrome was previously divided into 3 different types but is currently being described as a ST-segment elevation >2 mm in ≥ 1 right precordial lead, followed by a negative T-wave. The ST elevation in Brugada Syndrome is from the loss of action potentials in the epicardial myocytes.[128] This abnormal epicardial substrate can be found in the right ventricular outflow tract of the epicardium.[129] This mechanism of action is what leads to ventricular tachycardia, ventricular fibrillation, and sudden cardiac arrest. Brugada syndrome is speculated to be responsible for 20% of sudden deaths in patients with structurally normal hearts[130] and can be found in 5 in 10,000 people.[131]

The Division of Cardiology in Hartford Hospital completed a review article regarding Brugada Syndrome and exercise.[132] They were not able to find sufficient data specifically on the risks of exercise in Brugada Syndrome but regardless made recommendation to restrict patients with this syndrome from vigorous exercise. This was due to the worsening in ST abnormalities found during exercise with individuals with Brugada Syndrome, with the possibility that the ST abnormalities could lead to ventricular arrhythmias. The AHA/ACC recommends[124] that after a comprehensive evaluation by a cardiac geneticist, competitive sports participation does not have to be restricted but resumed with precaution after being asymptomatic for at least 3 months with thorough understanding of the disease, the prognosis, and the treatment. Patient should avoid dehydration, electrolyte abnormalities, and heat exhaustion to the best of their ability.[124]

Catecholaminergic Polymorphic Ventricular Tachycardia

CPVT is a genetic cardiac arrythmia centered around a delayed in afterdepolarization due to an upregulation of calcium influx, which is exacerbated by beta-adrenergic activity such as exercise.[133] The upregulation of calcium stems from genetic mutations that causes destabilization in the cardiac ryanodine receptors.[134] The estimated prevalence is 1 in 10,000, affecting mainly children between 7 and 12.[135] Symptoms, such as syncope, may resolve after being stimulated by acute emotion or exercise, but occasionally the ventricular tachycardia will progress to

ventricular fibrillation and cause sudden death.[135] Thirty percent of individuals with CPVT have had at least one cardiac arrest, and up to 80% have had at least one syncopal episode.[135]

Diagnostic testing includes a normal resting ECG, followed by an exercise stress test in order to evoke an acute adrenergic event.[135] AHA/ACC recommendation for previously symptomatic or asymptomatic CPVT patients include restriction from competitive sports, except for less strenuous sports such as bowling, billiards, golf, curling, riflery, and cricket (Class III, Level of Evidence C).[124]

Early Repolarization Syndrome

Early repolarization syndrome (ERS) can be defined as at least 2 consecutive inferior or lateral leads having positive S-wave deflection of at least 1-mm in amplitude above the baseline.[136] The mechanism of action for this syndrome consists of current imbalances between the endo- and epicardial layers.[137] In the epicardium, a larger transient-outward potassium and adenosine triphosphate-sensitive current, and a reduced inward sodium and inward calcium in the endocardium result in a greater net repolarizing outward current during the early phase of the myocardial action potential.[137] Prevalence of ERS is about 2%-5% of the population.[138] With a higher prevalence, early repolarization was thought to be a benign variant, but as of recently, it has been associated with increased sudden cardiac death. The syndrome commonly affects men, young adults, athletes, and African Americans.[138]

An ACC study[138] found nonanterior early repolarization to be very common among athletes and individuals involved in intense exercise training. The AHA and ACC do not provide any particular type of sport limitation for patients with ERS; but if a patient begins to experience symptoms, they should report to a heart rhythm specialist for further evaluation which could include ECG and exercise stress testing.[124]

Short QT Syndrome

Short QT syndrome is a cardiac channelopathy associated with a predisposition to atrial fibrillation and sudden cardiac death.[139] Cardiac workups typically reveal structurally normal hearts with ECGs with QTc intervals ranging from 248 to 300 milliseconds due to an underlying genetic gain-of-function mutations in 1 of the 3 voltage-gated potassium channel genes: KCNH2, KCNQ1, and KCNJ2.[140] This syndrome comes with a prevalence of 0.02%-0.1%.[141]

Short QT syndrome has been seen to have less strict exercise restrictions. This is likely due to it being a normal physiologic response for the QT interval to shorten when one's heart increase during exercise.[142] As with all of the cardiac channelopathies, the ACC and AHA[124] still recommends that if the patient develops symptoms, that the patient should refer to a cardiac geneticist and to restrict competitive sports until they are asymptomatic for at least 3 months.

Commotio cordis

Commotio cordis is a serious mechanoelectrical change that occurs in the heart because of mechanical trauma to the thoracic cage/heart that results in ventricular fibrillation and death.[143] It is considered to be one of the main causes of sudden cardiac arrest in young athletes,[144-146] generally adolescents with a mean age of 15 years.[144]

A combination of multiple factors has been noted to cause commotio cordis. Harder, smaller and more spherical objects that hit the thoracic cage around the heart has the highest risk for commotio cordis.[147-150] Objects that propagate at velocities greater than 40 mph were 68% more likely to cause sudden cardiac arrest.[151] Competitive sports that are well known to cause this include baseball, lacrosse, hockey and softball.[152]

According to Wiggers et al, ventricular fibrillation in commotio cordis starts in a very similar way to the electrical pathophysiology of long Q-T syndrome, "electric shock on t wave," in which EKG morphology is torsades de pointes.[153] Quinn et al described the intracardiac electrical pathology occurring in commotio cordis as a process that starts by a stretch to the myocardium which in turn causes an ectopic beat called "mechanical induced premature ventricular excitation." When this premature ventricular excitation occurs around 15-30 msec prior to the peak of T wave on electrocardiogram (early ventricular repolarization), it tends to cause ventricular fibrillation.[150,154]

Other authors elaborated on how we can prevent commotio cordis in our young athletes and sport players. According to Kumar et al, ventricular fibrillation was induced in 54% animal experiment without chest protectors, while it ranged 5%-60% with chest protection, he concluded that the thicker the chest protector material the higher the protection.[155] In 2017, the National Operating Committee on Standards for Athletic Equipment approved the world's first chest protector which intended to reduce the risk of commotio cordis in lacrosse and baseball players.[156] They have also developed a new way for evaluating the effectiveness of chest wall protectors in preventing commotio cordis.

According to the AHA/ACC, competitive athletes who survived commotio cordis may resume competition if cardiac workup does not show any underlying structural heart disease (Class IIa, Level of Evidence C).[157]

Conclusion

There are many factors that influence the risk of SCD. Age is one of the most important as there is a 100-fold decrease in individuals younger than 30 compared to individuals older than 35.[158,159] We have noted how one's exercises in relation to their baseline activity can influence risk with respect to underlying cardiac illness. Additionally, the presence of structural cardiac abnormalities can harbor fibrotic substrates and result in sustained ventricular tachyarrhythmias with ensuing SCD. Competitive sports and vigorous exercise are contraindicated in several arrhythmias, and in these conditions, sports requiring "burst" exertion should be especially avoided. With regards to screening tools to assess the safety of exercise in those with pre-existing cardiac disease, patients should be professionally evaluated prior to the exertional event in hopes to decrease the risk of arrhythmias and SCD.

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