

Athletic heart adaptation, pathological hypertrophy and sudden cardiac death

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Abstract

Cardiac hypertrophy has been continuing as the subject of the 'hottest' topic in research field for a long time since it creates pathophysiologic and clinical issues by structural and functional alterations of heart. Probably, it is explained by the prevalence of cardiovascular disorders in all-cause mortality. It seems that, on the basis of a contemporary data, the perception of 'benign' nature of the cardiac hypertrophy in athletic population is blurred. The improvement of imaging modalities and assessment tools largely contributed to comprehensive integration of scientific and clinical standpoints of athletic hypertrophy. Conventionally pathologic hypertrophy believed to be developed in a case of cardiovascular diseases, while the athlete's heart resulted by long-standing physical training. According to recent evidence, a gray zone of hypertrophy became emerged between physiological and pathological entities, which require further extensive investigations. The emerging huge challenges in sports cardiology are overtraining and doping abuse of elite athletes by the development of an excessive cardiac hypertrophy with the increased risk of cardiovascular adverse outcomes. Additionally, the higher prevalence of sudden cardiac death in sportsmen compared to sedentary matches, especially in case of athletes with known or suspected cardiovascular diseases necessitated scrupulous investigation of athletic heart syndrome. The development, variety and severity of cardiac hypertrophy fluctuate by sportive branch and training mode. The significance of problem is more emphasized when cohort studies represented survival differences by means of cardiovascular parameters between athletes and sedentary subjects and cardiac patients.

In this review, we aimed to represent recent physiological and clinical standpoints regarding to athletic heart syndrome as well as its difference from sedentary heart changes and pathological hypertrophy, its association with sudden cardiac death.

Key words: athlete's heart, pathological hypertrophy, maladaptive hypertrophy, sudden cardiac death, cardiovascular imaging, overtraining.

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Introduction

In sports medicine, hypertrophied myocardium with or without chamber dilation, predominantly of the left ventricle has been believed as a compensatory mechanism for maintaining the exercise-induced chronic overload. Otherwise termed as an athlete's heart, this entity necessitated thorough investigations due to development of structural, functional and electrical cardiac alterations parallel to athlete's career years (1, 2). Mainly, the aforementioned surveys were

concentrated on resolution of several issues. The first one is the difference between the pathological hypertrophy developed in sedentary patients due to underlying cardiovascular conditions and adaptive hypertrophy in the highly active sportive individuals. The detection of mild and subclinical forms of cardiac diseases, particularly inherited cardiomyopathies, generates a great challenge in both pre-participation and follow-up examinations of athletic population.

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The third question is the defining of controversial nature of the athletic heart syndrome whether adaptive hypertrophy shares or not the pathologic features of disease-based hypertrophy. Doping abuse and overtraining are other huge problems of sports cardiology with known and unknown deleterious outcomes. The fluctuating prevalence of sudden cardiac death (SCD) due presumably to underlying structural and electrical remodeling of athlete's heart presents the unresolved issues.

Early investigations revealed the different pathogenesis of athlete's hypertrophy in contrast to pathological one and defined as "physiological hypertrophy", thus structural and functional changes were proportional and hypertrophy regressed by detraining for a given period (3,4).

Furthermore, studies in sports cardiology presented the different features of left ventricular hypertrophy (LVH) depending on sportive branches. Despite the controversial nature of Morganroth hypothesis, two phenotypes of athletic

heart have not been fully rejected, rather modified according to static and dynamic effects of exercise on cardiac structures. According to that, eccentric hypertrophy (EcCH) develops mainly due to endurance-training or exercises with high dynamic and low static exertions (long-distance runners, cross-country skiers, etc.) while concentric hypertrophy (ConH) progresses in response to long-standing power training or exercises with high static demand (weightlifting, wrestling, etc.) (5-7, 10). Objectively, most of sportive disciplines consist of both endurance and resistance activity, so these branches are classified as mixed-training (boxing, football etc.). Another adaptive mechanism is seen in skill-training subjects (golfers, table tennis players, etc.) where functional and electrical alterations in cardiac activity observed despite the absence of structural cardiac remodeling in contrast to healthy sedentary individuals (9, 10).

For simplicity of understanding of cardiac adaptation in athletes, sedentary subjects and patients we proposed a diagram (Fig. 1).

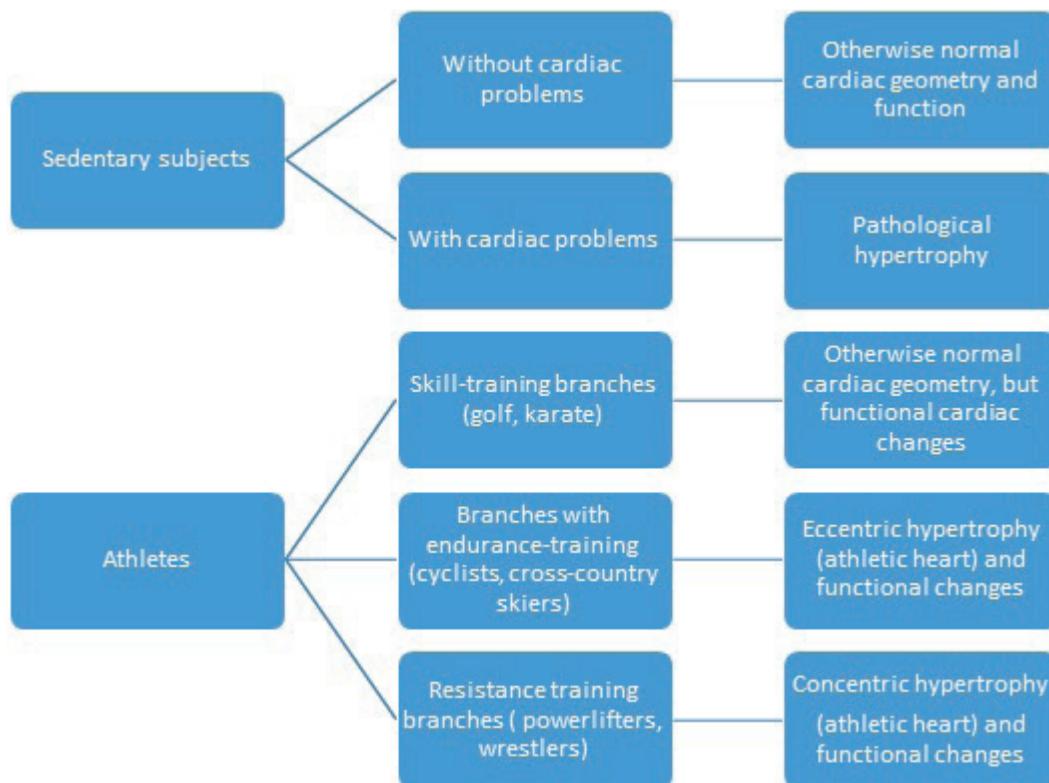


Figure 1. Different profiles of cardiac alteration in sedentary subjects, patients and athletes

In this review, we aimed to share the current standpoints in differential diagnosis of the athletic heart from pathological hypertrophy and the emergence of a maladaptive hypertrophy, as well as the nature of SCD in athletic population.

For data source we used PubMed, Science Direct libraries and Google Scholar with key words "cardiac hypertrophy", "left ventricular hypertrophy", "athlete's heart", "athletic

heart syndrome", "pathological hypertrophy", "hypertrophic cardiomyopathy", "hypertensive heart", "physiological hypertrophy", "maladaptive hypertrophy", "assessment of athlete", "sudden cardiac death", "mortality in athletic population", "training modes in sports". Both abstracts and full-text articles in English language included in our review with the preference of studies published within last decade.

Assessment and differential diagnosis of athlete's heart

Despite the latest controversies regarding to efficacy, meticulous cardiovascular pre-participation assessment of athletes remains crucial in defining the 'whole destiny' of sportsmen, though, establishment of false-diagnosis causes the unnecessary restriction from competition, while underassessment of comorbid pathology may lead to dramatic outcomes including SCD or development of heart failure (12, 13].

In a clinical sense, athletic heart stands for resting bradycardia and dilated chambers (1, 8]. Namely, decreased sympathetic tone, predominance of the parasympathetic system,

augmented stroke volume, decreased intrinsic heart rate and atrioventricular vagal conduction have been accepted as adaptive functional changes in professional athletes.

In contrast to physiological hypertrophy of professional athletes, pathological hypertrophy emerges due to increased afterload (e.g. essential hypertension) and myocardial diseases (e.g. hypertrophic cardiomyopathy) (3, 12]. An accurate delineation of underlying cardiac conditions is essential in competitive athletes, though intense physical training increases the risk of adverse cardiovascular events, including irreversible cardiac changes. Figure 2 depicts the basic differences between athletic heart and pathological hypertrophy.

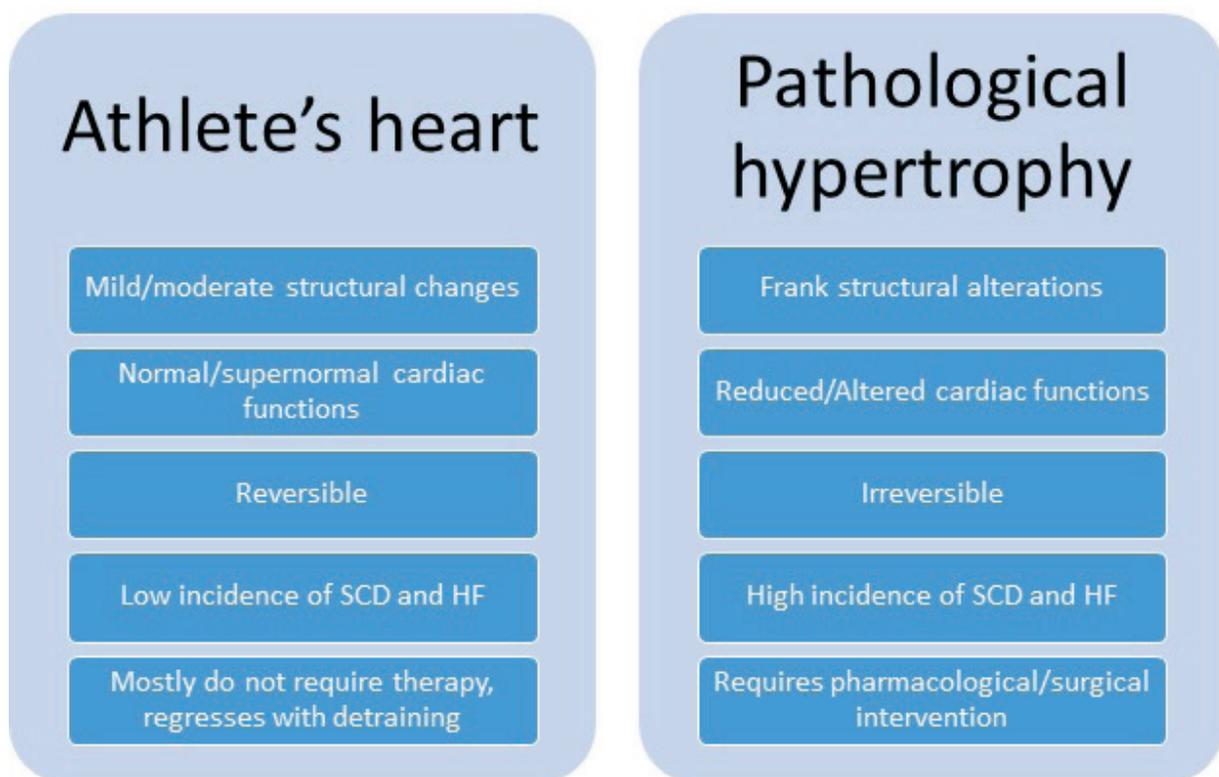


Figure 2. Characteristics of athlete's heart and pathological hypertrophy

HF – heart failure, SCD – sudden cardiac death

Hypertrophic cardiomyopathy (HCM) is the most encountered condition in young elite athletes, which plays a leading role in the eligibility and disqualification criteria for competitions (3, 12, 13]. Besides the HCM, number of inherited, acquired, ischemic and inflammatory cardiac diseases must be ruled out in athletes with cardiac hypertrophy.

Besides the 14-point standardized history and physical examination, current guidelines strongly recommend 12-lead electrocardiography (ECG) and transthoracic echocardiography (TTE) in competitive athletes, particularly younger subjects (11-14].

Electrocardiography

A 12-lead surface ECG frequently shows increased vagal tone and nonspecific electrical axis deviations and repolarization abnormalities, along with normal patterns as evidence of physiological electrical remodeling in athletes (10, 15]. Table 1 highlights the normal and abnormal patterns of surface ECG according to recent evidence (15-17]. When the suspicious 'red signs' are reflected on first-line ECG, it necessitates further investigations of second-line options including Holter monitoring and exercise testing.

Table 1. Electrocardiographic features of athletic heart (modified from ref. 15-17)

	Normal ECG patterns	Abnormal ECG patterns
1	↑ vagal tone: SB, 1st dg AVb in elite athletes	Advanced AVb(II dg II type, 2:1 and complete AVb, SA and SP (≥3000mc)
2	ERP predominantly in V5-V6 leads with concave STE commonly in males, blacks and those with LVH	Pathological Q-wave (>25% of R), except AvL, Any ST depression
3	Isolated SLC of LVH in asymptomatic athletes	Upright T-wave of AvR+TWI in V5-V6 shows apex pathology
4	TWI in V1-V3 for athletes<16years	Any TWI with preceding depression
5	TWI preceded by concave STE or J-point elevation in blacks	TWI in Caucasians and athletes>16 years old
6	RAD or LAD along with group 1 features (sinus bradycardia etc.)	TWI in two contiguous lateral and inferior leads
7	Voltage criteria for LAE, RAE, RVH along with group 1 features	LBBB (always) RBBB+RA and QRSd≥140mc
8	QTc<470 ms for males and <480 ms for females without Tnotch. or PPEX	QTc≥500 ms is obvious LQTS, 460-490 ms+syncope, family history of SCD, LQTS in 1st line relatives, Tnotch. and PPEX
9	Type 2 Brugada (saddle back) is non-specific	Type 1 Brugada (coved type) is always abnormal

AVb-AV block, ERP-early repolarization pattern, LAD-left axis deviation, LAE-left atrial enlargement, LBBB-left bundle branch block, LQTS-long QT syndrome, LVH-left ventricular hypertrophy, PPEX-paradoxical prolongation with exercise, RA-repolarization abnormalities, RAD-right axis deviation, RAE-right atrial enlargement, RBBB-right bundle branch block, RVH-right ventricular hypertrophy, SA-sinus arrest, SB-sinus bradycardia, SCD – sudden cardiac death, SLC-Sokolow-Lyon criterion, SP-sinus pause, STE-ST segment elevation, Tnotch.-T notching, TWI-T-wave inversion

Echocardiography

Echocardiography has a fundamental role in accurate evaluation of structural and functional status of athletic heart, as well as in diagnosis of underlying structural heart disease. Non-invasiveness, cost-effectiveness and widely availability favor the TTE being a first-line imaging modality. Measurement of wall thickness and chamber dimensions and evaluation of left ventricular mass (LVM) identifies the heart geometry by one of the following phenotypes: normal geometry, EcCH, ConH and concentric remodeling (ConR) (Table 2) (18).

As known, EcCH ensues a total increase in left ventricular mass LVM and chamber dilatation despite the normal relative wall thickness (RWT), whereas, ConH is characterized by

increased both LVM and RWT (8, 18]. According to recent recommendations RWT can be calculated by formula $2 \times \text{PVD} / \text{LV EDD}$ (where PVD stands for diastolic posterior left ventricular dimension and LV EDD is left ventricular end-diastolic dimension) and LVM indexed to body surface area (LVMI) obtained by ASE/Penn methods in linear measurements or by direct 2D options (area-length). RWT of 0.42 and LVMI of 95 and 115 gr/m² respectively for female and male subjects are established as the cut-off values. Currently there are no strictly recommended linear or 2D options for LVM evaluation in athletes. Despite the 3D echocardiography derived results well correlated by cardiac magnetic resonance (CMR), no cut-off values have been established (18].

Table 2. Types of left ventricular hypertrophy and remodeling*

Cardiac geometry	RWT	LVM (gr/m ²) (F and M)
Normal geometry	≤0.42	≤95 and ≤115* (≤88 and ≤102 ¹)
Concentric remodeling	>0.42	≤95 and ≤115 (≤88 and ≤102)
Concentric hypertrophy	>0.42	>95 and >115 (>88 and >102)
Eccentric hypertrophy	≤0.42	>95 and >115 (>88 and >102)

*modified from reference 18. under Creative Common license, F – female, LVM - left ventricular mass, M-male, RWT - relative wall thickness

Besides the measurement of structural parameters, echocardiography is a valuable tool for assessment of systolic and diastolic functions. Most studies revealed normal systolic indices and normal/supernormal diastolic parameters in elite athletes (18, 19]. According to Finocchiaro et al. tissue Doppler imaging (TDI) diastolic function was supernormal in 30% of athletes, reduced TDI lateral E' velocity was found only in 0.5% out of 1510 athletes, particularly in athletes >25 years old and with dilated chambers (20].

Nevertheless, suboptimal acoustic window, incomplete assumption of cardiac geometry especially of right chambers, inadequate assessment of cardiac functions necessitated the emergence of new techniques such as speckle tracking (STE) and three-dimensional echocardiography (3DE).

Strain and strain rate imaging modalities significantly improved the evaluation of athletic heart besides the subclinical myocardial dysfunction, HCM, restrictive diseases of myocardium and adverse effects of cancer chemotherapy, conditions that require thorough assessment of cardiac function, especially in early diagnosis (21-23]. According to recent guidelines, reference value of global longitudinal strain (GLS), the most reliable and robust marker of left ventricular systolic function fluctuates around -20% in accordance

with inter-vendor variability (18, 24]. Most of conducted investigations in athletic population revealed normal GLS values in contrast to healthy sedentary controls (21, 23-26]. In a study of Zebrowska et al, basal circumferential strain (BCS) and basal rotation (BR) were significantly altered ($p < 0.05$) in endurance athletes with LVH in contrast to athletes and sedentary controls without LVH, and considered as a predictive marker of cardiovascular morbidity (26]. According to some researchers, the left atrial strain parameters observed as independent factors of LVH, left atrial size and filling pressures in athletes with enlarged atria (27].

Despite the diagnostic difficulties, echocardiography enables the differentiation of athlete's heart from inherited myocardial diseases by structural and functional features (Table 3) (28). According to that, modest increase of walls and normal or proportional dilatation of chambers along with normal/augmented functions favor the diagnosis of athletic heart. Asymmetric hypertrophy with reduced left ventricular cavity and decreased diastolic function confirms HCM, whereas reduced GLS during effort indicates non-compaction cardiomyopathy. Arrhythmogenic right ventricular dysplasia (ARVD) is mainly presented by asymmetric right ventricular dilatation and wall motion abnormalities.

Table 3. Echocardiographic differences between athletic heart and cardiomyopathies*

	Athlete's heart	HCM
LV EDD	>54mm	≤45mm
LV volume/mass	normal or ↑	reduced
Mitral E' lateral	normal or ↑	reduced
LV RS and CS	normal or ↑	decreased
	Athlete's heart	LVNC
Trabeculation location	apical	mid-cavity
Mitral E' lateral	normal or ↑	normal or ↓
LV GLS at rest LV GLS at effort	normal/mild ↓ normal or ↑	normal or ↓ reduced
	Athlete's heart	ARVD/ARVC
RV enlargement	global	early RVOT dilation
Motion abnormalities	no	yes
Volume ratio RV /LV	<1	≥1

*modified from reference 28 under Creative Common license

ARVD/ARVC-arrhythmogenic right ventricular dysplasia/cardiomyopathy, CS-circumferential strain, GLS-global longitudinal strain, HCM – hypertrophic cardiomyopathy, IVS-interventricular septum, LV-left ventricle, LV EDD-left ventricular end-diastolic diameter, LVNC-left ventricular non-compaction, RS-radial strain, RV-right ventricle, RVOT-right ventricular outflow tract

Besides the sophisticated assessment of cardiac structures, 3DE revealed augmented systolic indices owing to subendocardial and mid-wall contractions in top-level endurance athletes (29). Lakatos et al. published the considerable gender difference in left atrial adaptation to exercise and revealed that pronounced morphological and functional remodeling of left atrium were independent predictors of exercise capacity (30).

Cardiac magnetic resonance imaging

Cardiac magnetic resonance imaging (CMRI) substantially improved the diagnostic workup of cardiac hypertrophy. A cut-off value of diastolic wall to volume ratio of $<0.15 \text{ mm} \times \text{m}^2/\text{ml}$ differentiates the athletic heart from all forms of pathological hypertrophy with 99% specificity (31). Late gadolinium enhancement option of CMRI is valuable tool for the detection of myocardial fibrosis, a morphological hallmark of pathological hypertrophy (18, 24).

Maladaptive athletic heart and pathological hypertrophy

Several studies reported the existence of difference in indices of hypertrophy and functional parameters of athlete's heart and pathological hypertrophy (3, 8, 16). These differences are the evidence of limitations of upper boundaries of physiological athletic hypertrophy.

While according to Pelliccia et al., the reference ranges of LV EDD are established as 55-63 mm and left ventricular wall thickness (LVWT) - ≤ 13 mm, some studies on Caucasian athletes recorded the upper value for LVWT up to 14mm to 16mm, and some authors recommended LV EDD and LVWT in elite male athletes as 14mm and 65mm, for females 11mm and 60mm, respectively (32, 33).

In fact, hypertrophy parameters largely depended on the sportive branch, training mode and gender of athletes. This condition has been supported by long-term longitudinal and cross-sectional investigations. One study in which 3,500 athletes were screened, revealed the TWI on ECG and LVH with non-dilated heart chambers on TTE consistent with HCM in 0.08% of athletes (3 out of 53 with LVH). It is noteworthy that none of them had HCM in their family (34). A longitudinal study conducted on 114 Olympic athletes on long-term uninterrupted intensive training, represented significant enlargement of left atrium and mild enlargement of aortic root while no pathologic alterations were observed in systolic function, regional wall motion, LVMI, and filling pressures of left ventricle (35).

However, the obtained results have not fully advocated the innocence of excessive cardiac hypertrophy in elite athletes. Recently, Henshen et al. reported the enlarged cardiac chambers of cross-country skiers (36). According to current results, hypertrophic maladaptation in athletes exceeding normal limits has been included into gray zone between

physiological and pathological entities. As the supporting criteria of gray zone hypertrophy, pathological Q waves on ECG, $\text{VO}_2\text{max} < 50 \text{ ml/kg/min}$ by cardiopulmonary exercise testing, $\text{LVWT} > 16 \text{ mm}$, diastolic dysfunction (septal $E' < 9 \text{ cm/s}$, $E/E' > 15 \text{ cm/s}$), $\text{LVEDD} < 48 \text{ mm}$ by TTE and presence of late gadolinium enhancement by CMRI were proposed (37, 38). In Figure 3, we represented the HCM-approached mega-hypertrophy in a gray zone due to increased risk of adverse cardiovascular outcomes.

Accordingly, disproportionate mass increase in the heart, cardiomyocyte deformation, inflammation, myocardial fibrosis, diastolic dysfunction and decreased cardiac output have been considered as markers of excessive cardiac adaptation. However, as previously mentioned the hypertrophy values of physiological athletic heart and cardiomyopathy clearly differed. While wall thickness in an athlete's heart is $< 13 \text{ mm}$, it is indicated as $> 15 \text{ mm}$ for the maladaptive hypertrophy. While the LVEDD assessed as $< 60 \text{ mm}$ in an athlete, which is 20% larger than that of healthy sedentary person, it exceeded 70mm in maladaptive athletic heart. Despite the increased myocardial mass and volume, a HCM-approached athletic heart shows lower functional capacity (32, 33, 39).

On the other hand, an athletic heart within the gray zone is characterized by diverse phenotypes of mass increase and chamber dilatation. It is explained by variety of factors that carry athlete's heart to maladaptation. For example, in those who practice intensive endurance training for a long time, the situation shows mega-dilatation especially of left chambers; and excessive myocardial wall thickening develops in athletes of extreme resistance training. Some cases are presented by ARVD (arrhythmogenic right ventricular dysplasia) features and are predisposed to life-threatening ventricular arrhythmias (40, 41).

An experimental study conducted on mice models stated that the animals exposed to intermittent excessive exercise showed the stress-induced activation of pathogenic signaling pathways, a molecular trigger of heart dysfunction rather than physiological hypertrophic growth (42). Besides the HCM-approaching phenotype, excessive cardiac hypertrophy leads to additional adverse cardiovascular outcomes, such as arterial hypertension and atrial fibrillation (43). Furthermore, not only exercise type, but also factors such as age, ethnicity, gender, genetic predisposition have impact on maladaptation emergence (33, 43).

To date, due to ethical impossibility of conducting of experimental studies on athletes regarding the gray zone status of cardiac hypertrophy, general standpoint of maladaptation relies solely on results of experiments on animal models. The accumulation of more analogous findings in this regard can be expected to strengthen our views on excessive cardiac hypertrophy.

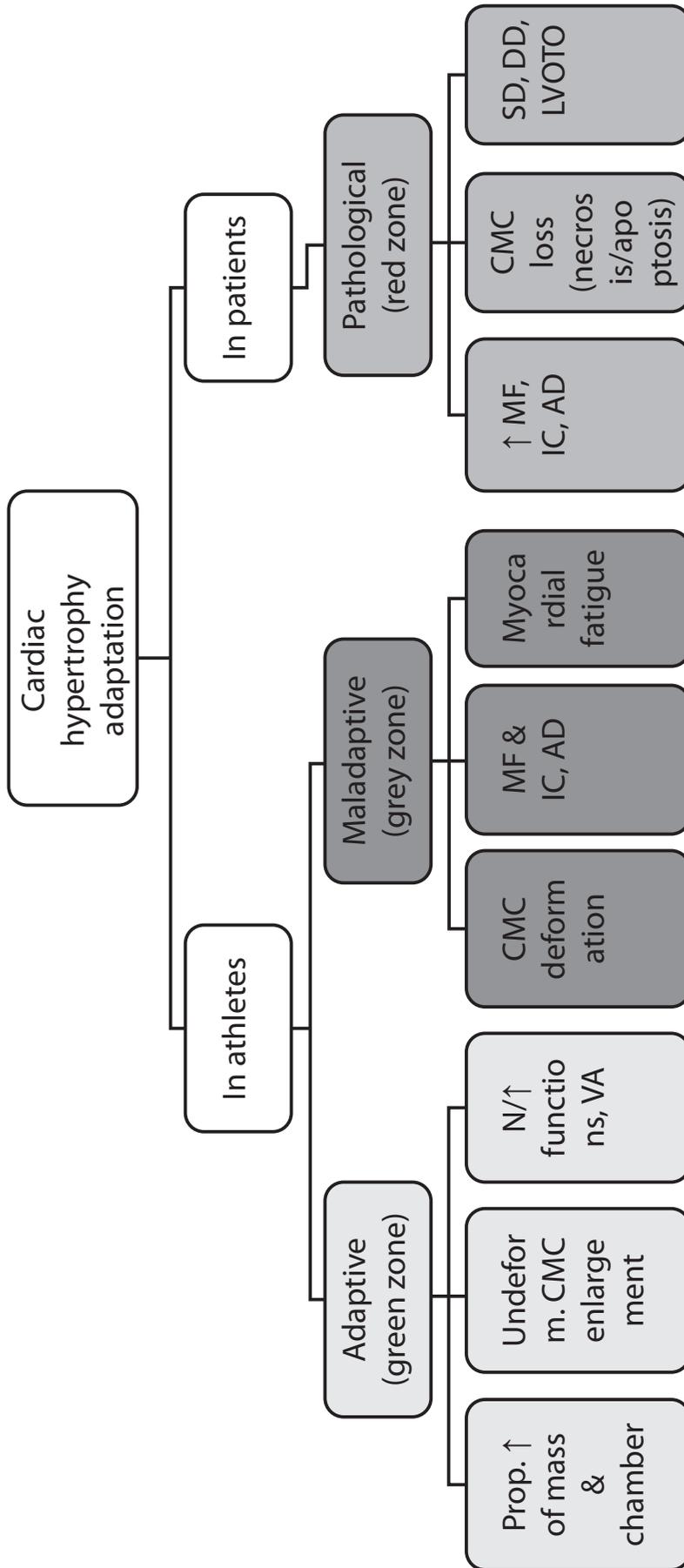


Figure 3. Cardiac adaptation profiles in athletes and patients

AD-arrhythmic dysplasia, N-normal, CMC-cardiomyocyte, DD-diastolic dysfunction, IC-inflammatory changes, LVOTO-left ventricular outflow tract obstruction, MF-myocardial fibrosis, SD-systolic dysfunction, VA-vagotonic adaptation, "Myocardial fatigue" refers to moderately expressed systolic and/or diastolic dysfunction

Sudden cardiac death associated with cardiac hypertrophy, exercises and other factors

Sports-related SCD is usually defined as sudden and unexpected death occurred during, or shortly after, exercise (with varying time intervals up to 24 hours) (13, 44, 45]. In fact, SCD is not a newly discovered condition in sports cardiology. Besides the creating a challenge for sports physicians and mass media, SCD influences the career of competitor and whole sports politics.

According to recent data, SCD incidence fluctuates from 0.75 in 100 000 to 1 in 40 000 and 1 in 80 000 athletic populations (46, 47]. It can be explained by variety of sports discipline, and overall health status of an athlete. Regarding to sports branch, SCD prevails in basketball players in US and in footballers in Europe (48, 49].

Furthermore, sex and ethnicity-based studies on SCD prevalence revealed the male preponderance over females and racial predilections in basketball players, though blacks were observed to be at three-time higher risk of SCD than Caucasians in US (48-51]. In young athletes, SCD incidence has been reported between 1:9000 and 1:300 000 (48].

Nowadays, SCD is listed in the most investigated research topics in spite of its infrequent incidence in general population. Although the factors revealed by the studies on SCD are quite widespread, full consensus has not been reached yet. It is probably explained by the limited possibilities of studies on the observed cases, though, a large body of the data is based on autopsy findings (49, 52]. Another important limitation is the insidious course of SCD that most of the cases occur without preceding symptoms (49, 53).

Even so controversial nature of SCD, some approaches and consensus agreements have been obtained. Some studies stated the occurrence of SCD in athletes depending on age aspects: younger athletes under 35 years suffered mainly from HCM or other hereditary conditions, whereas athletes over 35 years of age suffered from ventricular arrhythmias due to coronary artery disease or ARVD (45, 51].

Yet another important point is that HCM-approaching excessive hypertrophy existed in grey zone, which has been mentioned in previous section may be a primary underlying factor of SCD in overtraining athletes (37, 54].

The availability of examining the cardiac conduction system by electrophysiological studies (EPS) strengthened our

predictions about the SCD phenomenon (55]. One of the propositions related to the subject is that study of genetic ion channelopathies has been found as important diagnostic tool as genetic-molecular studies (56]. On the other side, excessive hypertrophy increases the risk of SCD by causing repolarization abnormalities and rhythm disturbances.

Recent retrospective studies revealed the relationships of vast majority of factors in the development of SCD (45, 52). According to literature review, we classified several factors considered to be underlying mechanisms for SCD occurrence (Fig. 4). Hereditary/genetic factors included HCM, dilated cardiomyopathy (DCM), ARVD/ARVC and other genetic cardiovascular diseases. Post-infarction scar formation, amyloidosis, antiphospholipid syndrome and etc. are listed as subsequent (acquired) factors. Issues related to gender, ethnicity and body constitution comprised as separate factors. Inadequate recovery, mode of training and sports branch are categorized in exercise-related factors. As can be seen from diagram, a single factor can be attributed to several groups, for instance HCM belongs to both hereditary (genotype+phenotype- condition), and sportive factors (high-intensity exercise worsens compensated systolic function).

In this section, we additionally concentrated on two factors: SCD linked to overtraining and doping/performance enhancer abuse. Per se, moderate exercise considered as beneficial in the management of many cardiovascular diseases. However, excessively intense and long-lasting exercise increased the likelihood of SCD in subjects with a genetic predisposition. More often long-standing overtraining, particularly endurance exercise is accompanied by development of myocardial fibrosis and coronary calcification contrary to what is expected in an athlete's heart (57). On the other hand, doping abuse and performance enhancing drinks are known to have fatal effects on the heart (58). It is stated that substances such as growth and thyroid hormone, anabolic steroids are related to excessive hypertrophy. Additionally, excessive use of caffeine, cocaine, besides its performance-enhancing effect, leads to risky consequences such as arrhythmia and hypertension (60, 61).

To sum up, according to recent evidence, frequent high-intensity exercise without adequate warm-up and cooling intervals, overtraining, inadequate regeneration, substance abuse together with underlying hereditary, genetic, subsequent and other factors gradually increases the occurrence of SCD.



Figure 4. Underlying mechanisms of sudden cardiac death

Conclusion

In contrast to athletes, sedentary patients with cardiac issues develop pathological hypertrophy. Different phenotypes of cardiac hypertrophy and numerous functional changes without structural remodeling may occur depending on exercise type. As well as, any cardiac hypertrophy in sportsmen should not be considered as normal or benign, unless maladaptive changes and underlying genetic, congenital conditions are ruled out. Excessive cardiac adaptation falls into grey zone, which is thought to have high tendency of transformation into pathologic hypertrophy. SCD is not only associated with vigorous physical activity in maladaptation, but develops on the background of relationships of several factors including genetic, congenital and acquired ones. SCD is not only associated with vigorous physical activity in maladaptation, but also develops on the background of relationships of several factors including genetic, congenital and acquired ones.

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