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ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
editorial_office@rsglobal.pl

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THE PARADOX OF SPORT: THE BENEFICIAL EFFECTS OF PHYSICAL ACTIVITY ON THE CARDIOVASCULAR SYSTEM VERSUS THE RISK OF ARRHYTHMIA

Alicja Babula (Corresponding Author, Email: alicjababula@onet.pl)

T. Marciniak Lower Silesian Specialist Hospital – Centre for Emergency Medicine, Wrocław, Lower Silesia, Poland

ORCID ID: 0009-0003-0573-5022

Bartosz Golis

Central Clinical Hospital of the Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0007-2968-6797

Anna Maria Gęsińska

Antoni Jurasz University Hospital, Bydgoszcz, Kuyavia-Pomerania, Poland

ORCID ID: 0009-0004-4336-8873

Krzysztof Czyżykowski

Antoni Jurasz University Hospital, Bydgoszcz, Kuyavia-Pomerania, Poland

ORCID ID: 0009-0006-8816-1811

Helena Szelka

University Clinical Hospital No. 2 of the Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0001-7142-341X

Paweł Edyko

Central Clinical Hospital of the Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0009-6764-3434

Wiktor Golus

University Clinical Hospital No. 2 of the Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0009-1930-9837

Katarzyna Andrzejewska

Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0001-6994-7505

Zuzanna Przybyła

Medical University of Łódź, Łódź, Łódzkie, Poland

ORCID ID: 0009-0009-4778-3106

Hubert Woźniak

Copernicus Memorial Hospital, Łódź, Łódzkie, Poland

ORCID ID: 0009-0002-9891-3248

ABSTRACT

In recent years, sport has become increasingly popular. It has long been known that regular physical activity is one of the most important factors in preventing cardiovascular disease. Many studies show that systematic exercise has many benefits: it leads to lower blood pressure, improved lipid profile, and beneficial adaptations in the structure and function of the heart. Endurance training induces physiological remodeling of the heart muscle, including enlargement of its chambers, increased left ventricular mass, and improved oxygen efficiency. This results in more efficient blood flow, lower resting heart rate, and increased heart rate variability. These parameters are an indicator of good autonomic balance.

However, over the years, we have seen increasing evidence that long-term, intense endurance training may carry certain risks. Numerous studies indicate an increased risk of arrhythmia in people who engage in intense sports. The most commonly described rhythm disorder in this population is atrial fibrillation, the incidence of which in endurance athletes may be several times higher than in the general population. Some retired athletes also experience cases of ventricular tachyarrhythmia, probably due to right ventricular overload and remodeling processes.

KEYWORDS

Atrial Fibrillation, Endurance Sport, Cardiovascular Adaptations, Arrhythmia, Heart Rate Variability, Cardiomyopathy

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Introduction

In developed countries, cardiovascular disease is the leading cause of death among adults. Physical activity and endurance sports are one of the cornerstones of cardiovascular disease prevention. Regular training has many benefits. In recent years, there have been increasing reports that VO₂max and HRV are predictors of longevity. Studies show that people who are regularly physically active have a higher average HRV than those who are less active. In addition, athletes undergo physiological remodeling, the nature of which depends on the type of physical activity (Di Gioia et al., 2024).

However, there is another side to the coin and certain risks: some endurance athletes may develop heart rhythm disorders. We refer to this phenomenon as the sports paradox — when potential benefits and risks coexist.

There is no doubt that an increased incidence of atrial fibrillation (AF) is observed in the athlete population. Systematic analysis and meta-analysis have shown that athletes have a higher risk of AF compared to non-athletes, with an odds ratio (OR) of ≈ 2.46 (95% CI 1.73–3.51) (Newman et al., 2021).

Although atrial fibrillation is the most common arrhythmia, it is not the only one of interest to researchers. Ventricular arrhythmias (e.g., NSVT, tachycardia) are also reported among athletes. In a study of 5,011 athletes without apparent cardiovascular disease, 367 (7.3%) had ≥ 1 premature ventricular beat (PVB) (Verdile et al., 2015).

Materials and methods

This paper is a review based on an analysis of the available scientific literature on the effects of physical activity, especially endurance training, on the cardiovascular system. Both the beneficial adaptive effects and the potential risk of arrhythmia and pathological cardiac remodeling were taken into account.

The literature review was conducted in the PubMed and PubMed Central (PMC) databases, using a combination of keywords: “endurance training,” “athlete's heart,” “cardiac remodeling,” “arrhythmia,” “atrial fibrillation,” “heart rate zones,” “cardiomyopathy,” and “exercise-induced adaptation.” The search was conducted between September and October 2025, but included publications from 2003 to 2025 in order to

obtain as comprehensive an overview of the knowledge in this field as possible. The initial selection included a total of over 60 items, of which 32 publications were selected for final analysis.

The aim of this study is to compile evidence on the beneficial effects of endurance training on the cardiovascular system and the potential risk of arrhythmia in athletes. The mechanisms of adaptation, the epidemiology of arrhythmia in the athletic population, and predisposing factors will be analyzed. This paper aims to highlight the beneficial effects of endurance training with simultaneous cardiac vigilance.

Results

A review of the literature has shown that regular endurance training has a significant, multidirectional effect on the cardiovascular system, including both beneficial structural and functional adaptations and a potential risk of cardiac arrhythmias in professional athletes. The collected data confirm the existence of the “sports paradox.” It is therefore crucial to individualize training loads and control exercise intensity in order to maximize benefits and minimize cardiac risks.

1. The beneficial effects of training

More and more studies document that endurance training brings direct and long-term benefits to the structure and function of the heart. It stimulates beneficial hemodynamic and metabolic adaptations: it increases cardiac output, improves aerobic capacity ($VO_2\max$), lowers blood pressure, and promotes better endothelial function and insulin sensitivity (Nystoriak and Bhatnagar, 2018). In addition, physical activity stimulates the molecular mechanisms responsible for angiogenesis, myocyte mass, and vascular elasticity, which protects against the development of cardiovascular pathologies. The authors note that moderate physical activity generally reduces the risk of cardiovascular disease and may indirectly protect against atrial fibrillation (Centurion et al., 2019). In another study, the authors emphasize the role of volume load in endurance training as a factor inducing physiological remodeling (Valenzuela et al., 2023). The heart adapts to exercise by enlarging the ventricles, moderately increasing myocardial mass, and improving diastolic function without negatively affecting systolic function. These adaptations result in more efficient heart function. We can observe a decrease in resting heart rate and an improved ability to respond to increased hemodynamic demand during exercise or stress.

1a. HRV

Heart Rate Variability is a measure of the variability of the intervals between successive heartbeats (R-R segments) at rest or during a specific period of time. Analysis of this parameter allows for the assessment of autonomic balance — that is, the ratio of parasympathetic to sympathetic activity. In summary, high HRV indicates better autonomic flexibility, a stronger parasympathetic tone, and a better ability to respond to physical exertion and stress. A review of the literature shows that regular endurance training and the skillful use of HRV in training monitoring can lead to increased HRV, which has numerous benefits for the cardiovascular system and recovery. Studies indicate that people who are regularly physically active have, on average, higher HRV than those who are less active (El-Malahi et al., 2024). The results suggest that athletes' hearts operate in a more “regenerative” mode at rest. In addition, studies indicate that controlling training load with HRV in mind can optimize adaptations and reduce the risk of overtraining (Manresa-Rocamora et al., 2021). In endurance athletes, higher HRV at rest correlates with better performance, and decreases in HRV may warn of overload, fatigue, or the need for recovery (Lundstrom et al., 2023).

1b. $VO_2\max$

$VO_2\max$ (maximum oxygen uptake) is an indicator of the maximum amount of oxygen that the body is able to take in, transport, and use during intense physical exercise. It is expressed in milliliters of oxygen per kilogram of body weight per minute (ml/kg/min) and is the gold standard for assessing cardiorespiratory fitness. $VO_2\max$ reflects the ability of the respiratory, cardiovascular, and muscular systems to work together to deliver oxygen to tissues and use it efficiently in aerobic metabolism. The literature increasingly emphasizes that high aerobic capacity is a strong predictor of better cardiovascular function and longer life. In a study of 579 men aged 42-60, whose $VO_2\max$ was measured twice at an interval of approximately 11 years, it was observed that each decrease of 1 mL/kg/min translated into an approximately 9% increase in the risk of death from all causes (Laukkanen et al., 2016). In turn, the large-scale FINRISK study showed that both subjective assessment of one's own physical fitness and estimated $VO_2\max$ were strongly inversely correlated with the risk of overall and cardiovascular mortality — people with higher fitness had a significantly lower risk of mortality (Solomon et al., 2018). A study on VO_2 at the oxygen threshold showed that higher values of this indicator were associated with lower mortality from both cardiovascular and all-cause causes (Kunutsor et al., 2017). Furthermore, in a recent review of longevity and aging mechanisms, the authors demonstrated a correlation between higher aerobic fitness and better telomere length maintenance — one of the biological explanations for why better fitness may translate into slower aging and longer life (Ryall et Denham, 2025).

1c. Resting heart rate

Resting heart rate (RHR) is a simple but very sensitive indicator of cardiovascular health and autonomic balance. A low RHR reflects increased parasympathetic activity and high cardiac efficiency, which requires fewer beats to maintain adequate cardiac output. Numerous epidemiological studies have shown that higher RHR values correlate with an increased risk of hypertension, coronary heart disease, and cardiovascular death. Regular endurance training is one of the most effective ways to lower RHR.

A study conducted in a large Swedish population showed that people with high levels of physical activity had lower RHR compared to inactive people. In addition, an increase in training load was inversely proportional to the risk of acute myocardial infarction. These results confirm that endurance exercise leads to lasting adaptive changes in the autonomic regulation of the heart, increasing its efficiency (Helleryd et al. (2023).

Resting heart rate is undoubtedly an important population biomarker of cardiorespiratory fitness, strongly correlated with activity levels and VO_2max parameters. Individuals with an RHR <60 bpm had a lower risk of cardiovascular disease, which highlights its diagnostic and prognostic significance. Thus, RHR may be a practical, inexpensive, scalable biomarker of fitness at the population level—useful for epidemiology and public health. (Gonzales et al., 2023).

A long-term cohort analysis involving nearly 1,000 participants observed over 48 years showed that a baseline RHR ≥ 90 beats/min was associated with significantly higher all-cause mortality (HR 1.60 compared to the 60-70 bpm group). The authors emphasize that both too high and too low resting heart rates over the long term may be a harbinger of poorer prognosis — meaning that it is worth maintaining an RHR in the range of approximately 60-70 bpm as “optimal” in this context (Cui et al., 2020).

A comparison of these data clearly indicates that regular physical activity—by lowering RHR—contributes to improved heart function, optimized autonomic balance, and a significant increase in life expectancy. The observed decrease in resting heart rate is therefore not only a marker of improved fitness, but also an independent protective factor against premature cardiovascular death.

2a. Athlete's heart

The “athlete's heart” is a classic example of exercise-induced cardiac remodeling (EICR), in which prolonged, intense physical exertion leads to the emergence of structural, functional, and electrical mechanisms that increase the efficiency of the circulatory system. In clinical practice, however, a challenge arises: in some athletes, the remodeling may be so significant that it overlaps with pathological features (e.g., mild forms of cardiomyopathy). This creates “gray areas” where it is difficult to clearly determine whether the changes are physiological or pathological. The authors propose an individualized approach: multimodal imaging and consideration of individual characteristics (gender, body size, type of sport, training history) in the interpretation of results (Danielian and Shah, 2022).

It should be emphasized that cardiac adaptations in athletes are heterogeneous — they depend on many factors: type and intensity of training, gender, body size, race, and current training status. In the case of endurance training, cardiac adaptations in athletes often manifest themselves in the form of left ventricular stretching (increased end-diastolic volume) with moderate muscle thickening, which corresponds to the eccentric hypertrophy model. In strength (static) sports, the load on the heart is mainly pressure (afterload), which theoretically promotes concentric hypertrophy (thickening of the wall without significant enlargement of the cavity). However, empirical data in strength athletes are less clear – many studies do not clearly confirm a dominant concentric increase. In mixed disciplines, where there is both a dynamic and a strength component, adaptations tend to be most complete – both wall thickening and enlargement of the heart chambers. It is worth noting that the intensity of adaptation depends on many factors: gender, body size, race, and training duration – which means that the image of an “athlete's heart” is not uniform and that differences between disciplines may overlap (Maxwell et Oxborough, 2025).

2b. Right ventricle

When discussing changes in the cardiovascular system in the context of sport, the right ventricle deserves special attention. Due to the unique anatomy and physiology of the RV, adaptive changes may be more pronounced than those in the left ventricle. Due to the fact that during intense exercise, pulmonary circulation and pulmonary artery pressure increase significantly, the RV experiences relatively greater wall stress than the left ventricle, which may trigger adaptive remodeling (Sanz-de la Garza et al., 2020).

Intense training can lead to an increase in RV volume, its dilation, and sometimes to a temporary decrease in systolic function (e.g., after very long exercise). The authors point out that it can be difficult to distinguish between physiological remodeling and early forms of diseases such as arrhythmogenic

cardiomyopathy. In this context, it is worth using a multimodal approach: assessment of ventricular geometry (e.g., RV inflow/outflow ratios), analysis of RV deformation (with particular attention to the free wall), identification of local dyskinesia or regional wall motion abnormalities, and monitoring of arrhythmia symptoms or myocyte biomarkers (Chivulescu et al., 2018).

The literature states that after long-term training, athletes often show an increase in RV volume, ventricular enlargement, or right ventricular hypertrophy, with preserved or slightly reduced systolic function as assessed by various parameters. In some cases, the regression of these changes after a period of reduced training is incomplete, suggesting that some RV adaptations may be permanent (D'Andrea et al., 2015).

Furthermore, observation of the stability or progression of changes over time (or regression after reduced training) may suggest whether the remodeling is adaptive or pathological.

2c. Hypertrophic cardiomyopathy

Hypertrophic cardiomyopathy (HCM) is a genetic disease characterized by hypertrophy (thickening) of the heart muscle, especially the left ventricle. This impairs the diastolic function of the heart. It is one of the main causes of sudden cardiac death in young athletes. Structural changes (e.g., left ventricular hypertrophy) can occur in both HCM and physiological cardiac remodeling in athletes, which makes diagnosis difficult. The authors emphasize the key role of echocardiography in assessing heart structure and function, but in doubtful cases, genetic testing is also recommended to identify HCM phenotypes (Bahlmann et al., 2015). Identifying and differentiating hypertrophic cardiomyopathy from “athlete's heart” is an extremely important and difficult challenge for physicians. Other tools that enable in-depth diagnosis of cardiomyopathy include advanced Doppler echocardiography techniques, strain/strain-rate studies, magnetic resonance imaging (Wasfy & Weiner, 2015). These tests can be used to assess, among other things, muscle relaxation velocity (E'), global longitudinal strain (GLS), and ventricular torsion dynamics.

Detraining may play an important role in the differential diagnosis between adaptive cardiac hypertrophy in athletes and pathological hypertrophy (e.g., hypertrophic cardiomyopathy). There have been reports of athletes with signs of hypertrophy in the so-called “gray zone” who underwent planned detraining, which led to regression of concentric hypertrophy, supporting the hypothesis that these changes are physiological in nature (Weiner et al., 2012). Thus, in cases where echocardiographic or morphological imaging does not allow for a clear distinction between adaptation and pathology, a period of reduced training load can be introduced as a “diagnostic test” — if the hypertrophy regresses, this indicates an adaptive nature, while if it remains unchanged, a pathological etiology becomes more likely.

3a. Arrhythmias

Cardiac arrhythmias are a diverse group of rhythm disorders resulting from abnormalities in the generation or conduction of electrical impulses in the heart muscle. They can range from mild, transient rhythm disturbances to potentially life-threatening tachy- or bradyarrhythmias. In the general population, the incidence of arrhythmias increases with age and the presence of cardiovascular disease, but they are also observed in young and physically active individuals. In recent years, there has been particular interest in the relationship between intense physical activity and the occurrence of cardiac arrhythmias, especially atrial fibrillation, which is the most common persistent arrhythmia in the adult population.

For this reason, the mechanisms and risk factors for atrial fibrillation in athletes, especially those training in endurance sports, are being analyzed more and more frequently.

3b. Atrial fibrillation—mechanism of development.

Atrial fibrillation is the most common arrhythmia in adults, including athletes. In the general population, AF is usually associated with hypertension, diabetes, aging, obesity, heart failure, ischemic heart disease, and other organic heart diseases. The pathophysiology of the development of this arrhythmia in athletes, who usually age in good condition and health, needs to be explained. Intense and chronic endurance training leads to structural and electrical changes in the atria of the heart, which may promote the development of atrial fibrillation. In the “substrate-modulator-trigger” model, athletes show atrial enlargement, fibrosis, and remodeling of atrial tissues, which promotes heterogeneous conduction and re-entry phenomena (Turagam et al., 2015). In addition, endurance training can initiate inflammatory processes, microtrauma to the myocardium, and oxidative stress, which together exacerbate the development of atrial fibrosis (Guasch et al., 2018).

At the same time, there is a modification of the autonomic regulation of the cardiovascular system. Athletes show increased parasympathetic tone at rest, which leads to a shortening of the atrial refractory period, and during exercise, increased sympathetic activity, which increases refractory dispersion and promotes electrical instability (Guasch et al., 2018). This combination of autonomic modulation facilitates the initiation of arrhythmias in an already altered substrate.

Finally, ectopic atrial excitations, especially from the pulmonary veins, are often cited as a triggering factor, which in the presence of a pathological substrate can trigger fibrillation (Estes & Madias 2017). In athletes, the increased frequency of such excitations may be the result of mechanical stretching of the atria or electrophysiological adaptations (Turagam et al., 2015).

In summary, structural (remodeling, fibrosis), autonomic (nervous imbalance), and trigger (ectopic) mechanisms interact in athletes, increasing susceptibility to atrial fibrillation, even in individuals without classic risk factors.

3c. AF risk

Numerous epidemiological studies and systematic reviews have shown that athletes, especially those training in endurance sports, have an increased risk of atrial fibrillation compared to non-athletes. In a meta-analysis of more than 60,000 participants, the risk of AF in athletes was more than twice as high as in the general population (odds ratio = 2.46; 95% CI 1.73–3.51) (Newman et al., 2021). These results are confirmed by an analysis that examined whether endurance sports also affect the risk of AF in women. It was confirmed that people who practice sports at a competitive level are more likely to develop atrial fibrillation than those who lead a sedentary lifestyle, even in the absence of classic cardiovascular risk factors, and this applies to both sexes (Drca et al., 2023).

In 2016, a group of long-distance swimmers was examined for the occurrence of AF. The athletes were over 60 years of age and were compared in terms of current diseases with a group of the same age. Atrial fibrillation was more common in swimmers, even though other diseases (hypertension, diabetes) were more common in the comparison group (Schreiner et al. 2016).

Another literature review showed that while moderate physical activity has a cardioprotective effect, very intense and chronic exercise can have the opposite effect, increasing the susceptibility of the atria to arrhythmias. The authors cited data from observational studies in which the incidence of AF in endurance athletes was up to several times (2–10 times) higher than in the untrained population (Centurión et al., 2019). It was suggested that this phenomenon may result from multifactorial pathophysiological mechanisms, including structural and electrical remodeling of the atria, increased parasympathetic activity, and the presence of ectopic foci. The authors emphasize that although the epidemiological evidence is not conclusive, there is a consistent trend indicating a higher risk of AF in endurance athletes compared to sedentary individuals.

3d. Arrhythmias other than atrial fibrillation in athletes

Atrial fibrillation is the most commonly reported arrhythmia in the athletic population, but a growing body of evidence suggests that prolonged, intense physical exercise may also promote other cardiac rhythm disorders, particularly ventricular arrhythmias. A study was conducted in which a group of 46 endurance athletes with recurrent ventricular arrhythmias were evaluated. In 59% of the subjects, features of structural right ventricular involvement were found, and in another 30%, suggestive changes were found. These results indicate that chronic cardiac overload during prolonged exercise can lead to right ventricular remodeling and the formation of an arrhythmogenic substrate conducive to the development of arrhythmias (Heidbüchel et al., 2003). During the observation period, dangerous ventricular arrhythmias were also reported, including cases of sudden cardiac death, confirming the potential clinical risk of this phenomenon.

Another study compared the incidence of ventricular arrhythmias in endurance athletes and non-athletes. No significant differences were found between the groups in terms of the number of isolated or complex ventricular excitations, suggesting that long-term training alone does not necessarily lead to an increased risk of arrhythmia in the absence of structural heart changes (Zorzi et al., 2018).

In 2015, an interesting study was conducted involving a group of over 5,000 athletes with no detected heart disease. Exercise-induced ventricular arrhythmias were found in approximately 7% of them. In most cases, these disorders were mild and did not have negative clinical consequences. In some athletes, the arrhythmias resolved after a temporary reduction in training intensity, which may indicate their functional nature (Verdile et al., 2015).

The collected data suggest that intense and prolonged sports activity may promote the occurrence of arrhythmias other than atrial fibrillation, but their frequency and clinical significance vary and depend on the nature of the training, its duration, and the presence of structural changes in the heart muscle.

Discussion

Regular physical activity is one of the most important elements in the prevention of cardiovascular disease. Numerous epidemiological studies confirm that regular moderate-intensity exercise is associated with a reduced risk of coronary artery disease, hypertension, heart failure, and cardiovascular death (Levine et al., 2014). The mechanisms of this effect include improved endothelial function, increased coronary reserve, weight loss, improved lipid and glycemic profiles, and beneficial effects on the autonomic nervous system. Regular training also leads to the so-called physiological remodeling of the athlete's heart, including a moderate increase in heart chamber volume, left ventricular muscle mass, and improved aerobic capacity.

Despite the documented positive effects of physical activity, the existence of the so-called “exercise paradox” is increasingly emphasized, according to which intense and prolonged endurance training may be associated with adverse changes in the heart. Many years of high-volume exercise promotes chronic volume overload, leading to stretching of muscle fibers and fibrosis of the atrial and ventricular walls. These changes may create a substrate for the development of arrhythmias, especially atrial fibrillation and ventricular arrhythmias (Drca et al., 2023). Studies have also shown that some endurance athletes have increased right ventricular wall stiffness and fibrosis, which can lead to repolarization disorders and the formation of ectopic arrhythmogenic foci (Heidbüchel et al., 2003).

This phenomenon is confirmed by clinical observations – some athletes have been found to have complex ventricular arrhythmias, sometimes of a potentially malignant nature, including cases of sudden cardiac death during exercise (Heidbüchel et al., 2003). In contrast, studies by Zorzi et al. (2018) and Verdile et al. (2015) suggest that not all arrhythmias in athletes are pathological – in many cases, they are mild, transient, and do not have negative clinical consequences. It has also been shown that reducing training intensity often leads to the resolution of arrhythmias, confirming their functional nature (Verdile et al., 2015).

Excessive exercise intensity may also contribute to the development of cardiomyopathy, especially in the right ventricle, referred to as “arrhythmogenic cardiomyopathy in athletes.” Unlike the physiological remodeling of an athlete's heart, these changes are pathological and lead to impaired systolic function and increased susceptibility to arrhythmias. This indicates that there is a fine line between the beneficial and harmful effects of physical exercise on the cardiovascular system.

In summary, moderate and regular physical activity has clear benefits for heart health, but excessive, long-term endurance activity can lead to adverse structural and functional changes in the heart muscle. This phenomenon should not discourage physical activity, but it does emphasize the need for individual adjustment of training loads and periodic cardiological evaluation of athletes, especially in endurance sports.

Conclusions

Regular physical activity is one of the most important factors in the prevention of cardiovascular disease and is an essential part of a healthy lifestyle. Numerous studies confirm its beneficial effects on endothelial function, lipid profile, blood pressure, body weight, and overall cardiac performance. Moderate physical activity leads to so-called physiological cardiac remodeling, characterized by an increase in heart chamber volume and left ventricular muscle mass while maintaining normal systolic and diastolic function. This type of adaptation is considered a natural and beneficial response of the cardiovascular system to regular training.

On the other hand, there is growing evidence that intense and prolonged endurance exercise can lead to pathological changes. Some athletes show myocardial fibrosis, atrial enlargement, and repolarization disorders, which may be arrhythmogenic. The most commonly reported arrhythmia in this population is atrial fibrillation, the risk of which increases proportionally to the duration and intensity of training. The possibility of other rhythm disturbances, such as ventricular arrhythmias, has also been demonstrated.

These data indicate that although physical activity is an indispensable element of heart disease prevention, excessive training load may in some situations have the opposite effect, promoting the development of arrhythmias and cardiomyopathy. Therefore, it is necessary to take an individual approach to training planning and to conduct regular cardiological examinations of people who practice competitive sports. Maintaining a balance between the benefits and potential risks of intense exercise is a key element in maintaining heart health in athletes.

Author's Contributions

Conceptualization: Alicja Babula

Methodology: Bartosz Golis, Alicja Babula

Software: Anna Gęsińska, Alicja Babula

Check: Helena Szelka, Alicja Babula

Validation / Check: Hubert Woźniak, Alicja Babula

Formal Analysis: Katarzyna Andrzejewska, Alicja Babula

Investigation: Krystian Czyżykowski, Alicja Babula

Resources: Paweł Edyko, Alicja Babula

Data curation: Wiktor Golus, Alicja Babula

Writing – rough preparation: Zuzanna Przybyła, Alicja Babula

Writing – Review and Editing: Anna Gęsińska, Alicja Babula

Supervision / Project Administration: Bartosz Golis, Alicja Babula

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