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Comparison of echocardiographic adaptations between left and right ventricles of sports person: A comprehensive review

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Abstract
Sports cardiology is a burning field to monitor and diagnose different conditions of hearts of athletes in relation to sports and training. A comprehensive attempt has been made to compare the echocardiographic adaptations between left and right ventricles in athletes engaged in various sports. Therefore, the purpose of the study was to differentiate physiological remodeling from underlying pathological conditions that can predispose to sudden cardiac death by comprising the adaptation between the right and left ventricles. The research reports were collected from various databases for synthesis and inference purposes. It integrates findings from multiple studies to provide an in-depth understanding of physiological remodeling in endurance, strength/power, and mixed sports. Adaptation of both the ventricles is seen in different sports the specific nature of these adaptations varies, with endurance training typically inducing eccentric left ventricular hypertrophy and right ventricular dilation, and strength training primarily leading to concentric left ventricular hypertrophy.

Keywords: Echocardiography, left ventricle, right ventricle, and sports

Introduction

According to Hippocrates, "That which is used develops; that which is not used wastes away" (Jones, 1923) [14]. This timeless concept is still very applicable in current sports science, especially when we look at how the human body, particularly the heart, responds to physical activity. One of the most prominent instances of physiological adaptation in athletes is cardiac remodeling, in which the heart alters its structure and function to meet the demands of prolonged exercise (Mihl *et al*., 2008; Palermi *et al*., 2023) [21, 25]. The demands of sustained activity cause the heart's structure and function to change, resulting in the "athlete's heart" (Fagard, 2003; Pluim *et al*., 2000; Palermi *et al*., 2023) [11, 28, 25]. They are not unintended consequences of training, but rather precisely controlled reactions to persistent physical stresses such as increased blood flow, metabolic load, and hormonal stimulation. Over time, these adjustments produce large quantifiable changes. The heart muscle thickens to increase pumping power, chambers expand to increase stroke volume, and both systolic and diastolic functions improve, increasing efficiency at rest and at peak effort, Henriksen *et al*., 1999 [12]; Venckunas *et al*., 2008 [37]; Sharma, Gupta, & Mukhopadhyay, 2024 [33, 32]. These enhancements enable the heart to meet the high circulatory demands of elite-level training and competition by delivering oxygen and nutrients more effectively to working muscles. This process of cardiac adaptation is complex and influenced by multiple factors. For instance, improvements in cardiac output and oxygen transport play a key role in increasing an athlete's maximal oxygen uptake (VO_2 max) which is a critical indicator of aerobic performance (Arbab-Zadeh *et al*., 2014) [1]. But the athlete's heart is shaped not only by training itself. A variety of intrinsic factors such as age, sex, and genetics contribute along with external influences including medication use some of which can elevate blood pressure and environmental conditions like atmospheric pressure and hypoxia (Palermi *et al*., 2023, Kleinnibbelink *et al*., 2021) [25, 16]. Importantly, the type and intensity of training dictate the nature of these cardiac changes. Endurance sports which involve prolonged increases in cardiac output typically led to volume overload and chamber dilation. In contrast, strength training involves short bursts of high blood pressure often resulting in concentric hypertrophy where the heart walls thicken (Mihl *et al*., 2008, Venckunas *et al*., 2008) [21, 37].

Athletes combining both endurance and resistance exercises often exhibit a mixed pattern of adaptation. In older individuals research also highlights the importance of training frequency which can significantly influence cardiovascular health outcomes (Raffin *et al*., 2019) [29]. To evaluate these adaptations echocardiography has become an essential non-invasive imaging tool used in sports cardiology (D'Andrea *et al*., 2019) [6]. It provides detailed insights into heart structure and function such as chamber size, wall thickness, and pumping efficiency helping clinicians differentiate between normal athletic remodeling and potentially dangerous conditions like hypertrophic cardiomyopathy (HCM) or arrhythmogenic cardiomyopathy (ACM) both of which increase the risk of sudden cardiac death (SCD) (Palermi *et al*., 2023) [25]. Accurate interpretation is critical because physiological changes must not be misread as pathology nor should genuine disease go undetected (Palermi *et al*., 2023) [25]. As emphasized by Sharma *et al*. (2024) [32] echocardiography continues to play a pivotal role in safeguarding athlete health through informed evidence-based cardiac screening. Sports cardiology has rapidly evolved into a dynamic and essential subspecialty within cardiovascular medicine. Once a niche area it is now a burning field that demands specialized clinical expertise particularly in the context of preparticipation screening prevention of sudden cardiac death and personalized exercise prescriptions. As D'Ascenzi *et al*. (2023) [25] emphasize the discipline is not only vital for managing competitive athletes but also plays a crucial role in guiding those disqualified from sports and sedentary individuals toward safe physical activity through tailored interventions (D'Ascenzi *et al*., 2023) [25].

Purpose of the Review

The aim of this review was to conduct an in-depth comparison of the echocardiographic adaptations seen in the left and right ventricles across various types of sport and sports person. By drawing on recent research we hope to clarify the complexities of athlete's heart remodeling and assist clinicians in distinguishing between healthy physiological changes and pathological conditions that may require intervention.

Cardiac Adaptations: Endurance vs. Strength Training

In sports, cardiac adaptation, also referred to as "Athlete's Heart," describes the anatomical and functional alterations in the heart brought on by frequent, high-intensity exercise that improve the heart's capacity to pump oxygen-rich blood throughout the body (Fagard, 2003; Pluim *et al*., 2000) [11, 28]. These changes, which include thicker heart walls and/or larger heart chambers, are a natural physiological reaction that results in a larger stroke volume and a stronger, more effective heart (Kovacs & Baggish, 2015) 1[8]. The demands of the sport determine the kind of adaptation, such as pressure-induced concentric hypertrophy from strength training or volume-induced eccentric hypertrophy from endurance training (Mihl *et al*., 2008) [21].

The "Morganroth hypothesis", proposed in 1975, suggested that the type of myocardial hypertrophy depends on the athletic training program. Although not universally applicable, this hypothesis posited that endurance exercise primarily induces eccentric LV hypertrophy characterized by LV dilation, while strength exercise promotes concentric LV hypertrophy with increased wall thickness (Morganroth *et al*., 1975) [23]. The adaptations that allow an athlete to exert the most energy in the specific discipline are what the body adapts to; therefore, there are also many hybrid athletes with aspects of both endurance and strength characteristics. An athlete's heart adapts differently to endurance and strength training; endurance training leads to eccentric hypertrophy with left ventricular dilatation, while strength training causes concentric hypertrophy with increased wall thickness. However, these adaptations often overlap, as both types of training can induce left ventricular hypertrophy to varying degrees (Mihl *et al*., 2008; Sharma, Gupta, & Mukhopadhyay, 2024) [33, 32].

- **Endurance Training:** Endurance sports such as long-distance running, cycling, and swimming involve sustained periods of elevated cardiac output and volume loading, leading to eccentric LV remodeling (Mihl *et al*., 2008; Sharma & Gupta, 2024) [32]. As Mihl *et al*. (2008) [21] state, the heart responds by increasing left ventricular internal diameter and left ventricular wall thickness. In line with this, endurance athletes may demonstrate a rise in heart rate and stroke volume while training (Mihl *et al*., 2008) [21]. It is thought that volume overload is what causes hypertrophy in the first place (Masoud *et al*., 2014) [19].
- **Strength Training:** Strength/power sports, such as weightlifting and combat sports, are characterized by intermittent bursts of intense activity that result in significant elevations in systolic and diastolic blood pressure. This pressure overload leads to concentric LV hypertrophy (Mihl *et al*., 2008) [21]. The intermittent characteristics of this training type do not allow for sustained energy levels and instead develop wall strength and thickness. It has been shown that though weightlifting is good for strength, there may be better alternatives for the athletic heart and blood pressure of the heart with resistance band training that cause a lower risk of hypertension (Melo *et al*., 2018) [20].

Left Ventricular Adaptations

Left ventricular adaptations to sport, identified by echocardiography, include structural changes like enlarged chambers and thickened walls, as well as functional changes that improve heart efficiency (Mihl *et al*., 2008; Venckunas *et al*., 2008; Sharma, Gupta, & Mukhopadhyay, 2024) [20, 37, 33, 32]. Endurance exercise often leads to eccentric hypertrophy, resulting in increased chamber volume and wall thickness, while weight training can result in concentric hypertrophy with thicker walls and normal chamber size. Improved diastolic function and higher stroke volume enhance the heart's blood pumping capacity (Mihl *et al*., 2008; Venckunas *et al*., 2008) [20, 37].

Studies consistently demonstrate that athletes, compared to sedentary controls, exhibit increased left ventricular mass (LVM) and wall thickness (Mihl *et al*., 2008; Venckunas *et al*., 2008) [20, 21, 37]. However, the specific pattern of LV remodeling varies depending on the nature of the sport (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]. The heart remodeling process can greatly influence the volume of oxygen the athlete may intake, therefore improving their ability to exert more energy (Mihl *et al*., 2008) [21]. It is key to have early stages of treatment of arterial complications as well before more damage can occur to the heart (de Araujo *et al*., 2013) [3].

Endurance Athletes

Echocardiographic findings in endurance athletes often include:

- Increased left ventricular end-diastolic diameter (LVEDD), (Mihl *et al*., 2008) [21].
- Increased LV mass (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37].
- Normal or supranormal systolic function (Mihl *et al*., 2008) [21, 21].
- Increased stroke volume (Mihl *et al*., 2008) [21].

Studies by Venckunas *et al*. (2008) [37] have found that long-distance runners had larger body size-adjusted LV diameters compared to basketball players, cyclists, and strength/power athletes, supporting the hypothesis that exercise-induced volume overload triggers myocardial dilation. In addition, some changes that occur in the electrocardiogram, including elevated heart rate and decreased repolarization, are normal for endurance athletes, as noted by Pelliccia *et al*. in multiple papers (Pelliccia *et al*., 1991, 1993) [26, 27]. Furthermore, there is adaptation to arterial and venous systems to improve output during performance (Fagard, 2001) [10].

Strength/Power Athletes

The concentric hypertrophic responses shown in the strength/power athletes include the following:

- Increased left ventricular wall thickness (LVWT) (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37].
- Normal left ventricular end-diastolic diameter (LVEDD) (Mihl *et al*., 2008) [21].
- Increased LV mass (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37].
- Normal or supranormal systolic function (Mihl *et al*., 2008) [21].

Haykowsky *et al*. (2002) [13] found that strength training aimed at increasing skeletal muscle power/strength/mass would not necessarily result in cardiac wall thickening. The variations in cardiac size, thickness, and mass suggest that there is no evidence of dichotomous cardiac adaptation to strength/power athletes (Haykowsky *et al*., 2002) [13]. This is why it is important for scientists to take into consideration some factors that come with it, such as genetics, age, gender, and ethnicity, to develop a test that can have more specific factors. As noted by Venckunas *et al*. (2006) [37], there may be some concentric hypertrophy within the heart mass in experienced distance runners. However, there can be many issues with the heart remodeling from weight training due to anabolic steroids that cause atherosclerosis (Santora *et al*., 2006) [31]. It is recommended to get evaluated by a specialist often and early to catch any diseases (Trachsel *et al*., 2015) [35].

Right Ventricular Adaptations

Right ventricular (RV) echocardiographic adaptations in athletes, particularly endurance athletes, include a combination of structural and functional changes, such as increased RV dimensions and wall thickness, and functional modifications like increased tricuspid annular displacement and velocity (Dawkins *et al*., 2021) [9]. Historically, research on athlete's heart has predominantly focused on the left ventricle. However, growing evidence suggests that exercise training also induces significant adaptations in the right ventricle (RV), particularly in endurance sports (Henriksen *et al*., 1999) [12]. Studies have demonstrated that endurance training leads to an increase in RV size, including diameter and area (Henriksen *et al*., 1999) [12]. Dawkins *et al*. (2021) [9] confirmed that structural remodeling of the right ventricle (RV) is a well-documented phenomenon in athletes with enhanced systolic pressure and systolic free-wall longitudinal mechanics.

Endurance Athletes

Endurance athletes often exhibit RV dilation and altered RV mechanics. Key echocardiographic findings include

- Increased RV end-diastolic volume (Henriksen *et al*., 1999 [12]; D'Andrea *et al*., 2015; Conti *et al*., 2021) [4].
- Increased RV end-diastolic area (Henriksen *et al*., 1999; D'Andrea *et al*., 2015) [12, 4].
- Increased tricuspid annular plane systolic excursion (TAPSE), (Henriksen *et al*., 1999) [12].
- Elevated RV systolic pressure, both at rest and during exercise (Dawkins *et al*., 2021) [9].
- A greater base-to-apex strain gradient (Dawkins *et al*., 2021) [9].

Kleinnibbelink *et al*. (2021) [16] showed that a lesser increase in RV fractional area change during acute exercise was associated with the increase in resting RV basal diameter at the completion of a training protocol. There is a relation of cardiac function of the RV to the ventricular remodeling and it may become an indicator to look out for before other factors begin to change (Kleinnibbelink *et al*., 2021) [16]. The right side of the heart may also undergo structural changes in conjunction with the left side as well (Henriksen *et al*., 1999) [12]. The aerobic training does give great advantages in the long run, as they have an increased efficiency in antioxidant defensive mechanisms. It has also been shown that regular exercise can increase the capacity of cells to perform efficiently in both heart and muscles and more (Rosa *et al*., 2005) [30]. In highly trained athletes, particularly those engaged in endurance sports, the right ventricle (RV) undergoes adaptive remodeling in response to increased hemodynamic demands (D'Andrea *et al*., 2015) [4]. This physiological adaptation includes enlargement of the RV, with greater inflow and outflow dimensions compared to sedentary individuals (D'Andrea *et al*., 2015) [4].

Strength/Power Athletes

The data on RV adaptations in strength/power athletes is not abundant. This can be an area for future research. More information is needed to confirm the structural adaptations for strength power athletes (Mihl *et al*., 2008) [21].

Distinguishing Physiological Remodeling from Pathological Conditions

One of the major challenges in evaluating the athlete's heart is differentiating physiological remodeling from pathological conditions that can predispose to SCD (Palermi *et al*., 2023) [25]. It is necessary to have a precise definition of the features of the athlete's heart and stringent criteria to optimize the clinical management of these subjects to be able to make a differential diagnosis with HCM, DCM, left ventricular noncompaction (LVNC), and ACM (Palermi *et al*., 2023) [25]. The challenge may be due to overtraining and can be resolved through proper treatment (Palermi *et al*., 2023) [25]. It is also important to investigate these issues in women (Karagjozova *et al*., 2017) [15]. Endurance and strength athletes exhibit eccentric hypertrophy, while HCM and ARVC present structural abnormalities and increased SCD risk. Advanced imaging, including strain and tissue Doppler, is crucial for accurate diagnosis. Echocardiographic screening distinguishes normal adaptations from dangerous pathologies, preventing misdiagnosis and ensuring cardiovascular safety in sports.

To differentiate between pathologic modification and physiologic remodeling, cardiac volumes and masses should be compared to reference ranges derived from CMR studies on healthy athletes and adjusted to factors, including type of sport, static and dynamic component, training hours per week, body surface area, age, gender, and ethnicity (Palermi *et al*., 2023) [25].

Multimodality Cardiac Screening

A step-by-step multimodality approach is crucial in differentiating athlete's heart from underlying pathology (Palermi *et al*., 2023) [25]. The process should encompass a range of diagnostic techniques and the evaluation of all clinical data (Palermi *et al*., 2023) [25].

- **First-line screening:** Medical history, physical examination, and electrocardiogram (ECG) (Palermi *et al*., 2023) [25].
- **Second-line evaluation**: When a suspicion of a structural CV disease is raised, an echocardiogram should be performed with an exercise test to see the full function (Palermi *et al*., 2023) [25].
- **Third-line evaluation:** With abnormal or uncertain indings from the previous 2 steps, the athlete must then go to high-cost and high-tech cardiac diagnostic techniques (Palermi *et al*., 2023) [25].

Among the new technologies in detecting cardiac dysfunctions, there are also tests to investigate wall strength of the ventricles and stress areas in an effort to better diagnose underlying problems. It is with the hope that more noninvasive tools can be created as the field continues to progress.

Echocardiographic Findings Tables

In sports cardiology, echocardiography is a crucial non-invasive imaging technique for evaluating the physiological changes in athletes' hearts and assisting in the differentiation of pathological conditions such as dilated cardiomyopathy or hypertrophic cardiomyopathy from normal athletic remodeling (D'Andrea *et al*., 2019) [6]. It is a key component of pre-participation screening to lower the risk of sudden cardiac death in athletes by precisely measuring changes in the left and right ventricles by giving comprehensive anatomical and functional data.

Integrating echocardiographic findings from Sharma, Gupta, & Mukhopadhyay, (2024) [33, 32], Mihl *et al*. (2008) [21], and Venckunas *et al*. (2008) [37], and Sharma *et al*. (2024) [32], the following tables summarize key echocardiographic parameters in athletes across various sports disciplines:

Table 1: Left Ventricular Echocardiographic Findings in Athletes

Parameter	Endurance Athletes (General)	Strength/Power Athletes (General)
LVEDD (mm)	Increased (Mihl *et al*., 2008; Sharma, Gupta, & Mukhopadhyay, 2024) [21, 33, 32]	Typically normal (Mihl *et al*., 2008; Sharma, Gupta, & Mukhopadhyay, 2024) [21, 33, 32]
LV Wall Thickness (mm)	Increased (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]	Increased (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]
LV Mass (gms)	Increased (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]	Increased (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]
LVEF (%)	Normal to supranormal (Mihl *et al*., 2008) [21]	Normal to supranormal (Mihl *et al*., 2008) [21]
LA Diameter (mm)	Increased	Data missing
E/A Ratio	Normal or Increased	Lower

LV-Left Ventricle, LVEDD-Left Ventricular End Diastolic Diameter, LVEF-Left Ventricular Ejection Fraction, LA-Left Atrial, E/A Ratio-Early Diastolic Filling Velocity to Late Diastolic Filling Velocity ratio

Table 1 reveals that endurance athletes tend to have a larger heart size, as reflected by a large LVEDD, than strength/power athletes as a result of long periods of low-intensity cardiovascular exertion (Mihl *et al*., 2008; Venckunas *et al*., 2008; Sharma, Gupta, & Mukhopadhyay, 2024) [21, 37, 33, 32]. LV mass tends to increase in both groups (Mihl *et al*., 2008; Venckunas *et al*., 2008) [21, 37]. However, diastolic function and pressure vary according to the type of sport. Furthermore, some factors are still missing, such as LA diameter or E/A ratio. This table is missing more recent information as well, such as longitudinal analysis that may be done. To improve redox balance, the most used type of exercise is the aerobic type; therefore, that gives advantages to the endurance group as well.

Table 2: Right ventricular echocardiographic findings in athletes

Parameter	Endurance Athletes (General)	Strength/Power Athletes (General)
RV End-Diastolic Area (cm^2)	Increased, Henriksen *et al*., 1999 [12]; D'Andrea *et al*., 2013 [5]; D'Andrea *et al*., 2015 [4]; Conti *et al*., 2021 [4]	Limited evidence, likely less pronounced (Mihl *et al*., 2008) [21]
RVOT Diameter (mm)	Increased, Henriksen *et al*., 1999 [12]; D'Andrea *et al*., 2013; [5] D'Andrea *et al*., 2015 [4]	Limited evidence, likely less pronounced (Mihl *et al*., 2008) [21]
TAPSE (mm)	Increased, Henriksen *et al*., 1999 [12]; D'Andrea *et al*., 2013 [5]	Limited evidence, likely less pronounced (Mihl *et al*., 2008) [21]
RVFAC (%)	Increased, Kleinnibbelink *et al*., 2021; D'Andrea *et al*., 2013 [16]	Data missing
RV SBP (mmHg)	Increased, Dawkins *et al*., 2021; D'Andrea *et al*., 2013 [5]	Data missing
RAA	Increased	N/A

RV-Right Ventricle, RVOT-Right Ventricular Outflow Tract, TAPSE-Tricuspid Annular Plane Systolic Excursion, RVFAC-Right Ventricular Fractional Area Change, SBP-Systolic Blood Pressure, RAA-Right Atrium Area

Table 2 reveals that there are some structural changes in the endurance athletes, including RV dilation and changes in pressure load (Dawkins *et al*., 2021; D'Andrea *et al*., 2013; Henriksen *et al*., 1999; Kleinnibbelink *et al*., 2021) [9, 5, 12, 16]. Sharma *et al*. (2024) [32] mentions echocardiography as an effective tool for cardiac anatomy with good non-invasive properties. More research must be done for other types of sports. Furthermore, some important measurements and diastolic functions, such as RVFAC and RV SBP, still need to be taken into consideration. This study is limited in the range of knowledge that we have, and further investigation with other modalities needs to be taken into account to understand these phenomena. Furthermore, sex can also play a role, and it is shown from experimentation that heart gains occur more effectively in female hearts (Konhilas *et al*., 2004) [17].

Conclusion
The athlete's heart is a fascinating example of the cardiovascular system's plasticity and ability to adapt to diverse physiological demands. While both the left and right ventricles undergo remodeling in response to exercise training, the specific nature of these adaptations varies depending on the sport, with endurance training typically inducing eccentric hypertrophy and RV dilation, while strength training primarily leads to concentric hypertrophy. A comprehensive understanding of these differential adaptations, coupled with a systematic approach to clinical evaluation, is essential for distinguishing physiological remodeling from underlying pathological conditions, ensuring the health and safety of athletes across various disciplines. As technology moves forward and diagnostic evaluations evolve, future exploration of other factors may allow for more precision and a better comprehension of cardiovascular health.

Recommendation
Special attention will be given to echocardiographic evaluation of both systolic and diastolic function, underscoring its importance in the comprehensive cardiovascular assessment of athletes.

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