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Integrating Electrical and Structural Cardiac Adaptations in Professional Basketball Players to Enhance Training Efficiency and Recovery

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Abstract: Professional basketball players undergo high-intensity training that promotes cardiac adaptations. This literature review summarizes current evidence on electrical and structural cardiac remodeling in professional basketball players and explores implications for training and recovery. Structural changes, such as ventricular enlargement and atrial remodeling, are common in this population. Early repolarization patterns are frequently observed, reflecting advanced physiological adaptation rather than isolated abnormalities. Integrating cardiovascular screening with performance and recovery monitoring can help optimize individualized training strategies, improve recovery, and maintain athlete health. This synthesis provides practical insights for sports medicine professionals and coaches to enhance player performance while minimizing cardiac risk.

Keywords: Athlete's heart; Cardiac remodeling; Early repolarization; Professional basketball; Recovery management

Introduction

Professional basketball is a high-intensity intermittent sport characterized by repeated sprints, jumps, accelerations, decelerations, and rapid changes of direction performed with limited recovery intervals. Although many decisive actions are predominantly anaerobic, successful performance also depends on adequate aerobic capacity to sustain repeated high-intensity efforts and to accelerate post-exercise recovery. Therefore, understanding cardiovascular adaptation in professional basketball is important not only for performance profiling, but also for training prescription and recovery management in elite players (Claessen et al., 2020; D'Andrea et al., 2021; Engel et al., 2016).

Long-term intensive training gives rise to the well-recognized phenotype of the athlete's heart, which encompasses electrical, structural, and functional remodeling, including chamber enlargement, increased wall thickness, and autonomic adaptations with preserved or enhanced cardiac performance. However, these physiological changes may overlap with cardiomyopathies and other pathological substrates associated with sudden cardiac death, creating an important diagnostic gray zone in highly trained athletes. For this reason, contemporary athlete-specific electrocardiographic criteria and multimodality

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cardiovascular assessment are essential to distinguish benign remodeling from clinically significant disease (Gottlieb et al., 2021; Halson, 2014a; Haydar et al., 2000).

Basketball-specific evidence suggests that professional players may exhibit a particularly distinctive remodeling profile because of their extreme anthropometry and chronic exposure to elite training loads. In US professional basketball players, left ventricular cavity dilatation was reported in 36.5% and left ventricular hypertrophy in 27.4%, indicating that marked structural adaptation is common in this population. Complementing these structural findings, abnormal T-wave inversion was identified in 6.2% of NBA athletes and was associated with smaller ventricular cavity size and increased relative wall thickness, whereas in female professional basketball players training-related ECG findings were frequent (78.6%) but abnormal ECGs were relatively uncommon (4.6%), emphasizing the importance of sex- and sport-specific interpretation (Sharma et al., 2018; Stumpf et al., 2016).

These observations have implications that extend beyond cardiovascular screening alone. In elite basketball, training and competition loads must be balanced against recovery status, as load monitoring helps determine whether athletes are adapting appropriately and may reduce the risk of maladaptation, excessive fatigue, illness, and injury. Recent monitoring data in professional female basketball players demonstrated higher weekly load, monotony, and strain during the preseason, whereas perceived recovery was poorer during the in-season period, underscoring the need for individualized planning across the competitive calendar. Accordingly, this literature review aims to synthesize current evidence on electrical and structural cardiac remodeling in professional basketball players and to discuss how these findings may inform more precise training and recovery optimization (Sharma et al., 2018; Zimmermann et al., 2022).

Method

Study Design and Search Strategy

This study was conducted as a structured narrative literature review on electrical and structural cardiac remodeling in professional basketball players, with particular emphasis on early repolarization, echocardiographic adaptation, exercise performance, and their implications for training and recovery management. The narrative review approach was selected because the available literature varies in study design, participant characteristics, cardiac assessment methods, and reported outcomes, making qualitative synthesis more appropriate than meta-analysis. To improve clarity and methodological transparency, the review process was organized through a structured sequence of literature identification, screening, selection, and thematic synthesis.

A literature search was performed in PubMed/MEDLINE, Scopus, and Web of Science from database inception to March 2026. However, greater emphasis was placed on studies published within the last ten years to ensure relevance to contemporary sports-cardiology practice, particularly in relation to current diagnostic perspectives on athlete's heart, electrocardiographic interpretation, and sports-related cardiac adaptation. The search used combinations of the following keywords: "athlete's heart," "basketball players," "professional basketball," "early repolarization," "electrocardiography," "echocardiography," "cardiac remodeling," "cardiopulmonary exercise testing," "training load," and "recovery." Reference lists of relevant studies and review articles were also screened manually to identify additional publications.

Studies were prioritized if they specifically involved basketball players and reported findings related to electrical remodeling, structural cardiac adaptation, echocardiographic parameters, electrocardiographic patterns, cardiopulmonary exercise performance, training load, or recovery-related cardiovascular outcomes. Studies involving non-basketball athletes were not included as primary evidence, but they could be used selectively as contextual comparison when necessary to explain broader concepts in sports cardiology. Data extraction was performed by the author using a structured extraction format that included study characteristics, participant profile, basketball level, cardiac assessment method, key findings, and relevance to training or recovery management. The extracted findings were then grouped thematically into electrical remodeling, structural remodeling, exercise performance, and practical implications for athlete monitoring, training, and recovery.

Eligibility Criteria and Synthesis

Studies were considered eligible if they were published in English, involved competitive or professional basketball players or athletic populations with extractable sport-cardiology findings relevant to basketball, and reported electrical findings, structural cardiac parameters, exercise capacity, or training/recovery-related implications. Original observational studies, cohort studies, cross-sectional studies, and clinically relevant review articles were considered for inclusion, while case reports, conference abstracts without sufficient methodological detail, and studies unrelated to cardiac adaptation in athletes were excluded. Data were extracted narratively on study

characteristics, athlete population, ECG findings, echocardiographic or imaging markers, cardiopulmonary exercise variables, and the practical implications for training monitoring and recovery planning. Because of expected heterogeneity in study design, athlete characteristics, and reported outcomes, findings were synthesized qualitatively rather than by meta-analysis, with particular attention to the coupling between electrical patterns and structural remodeling in the athlete's heart. The focus on multimodality interpretation is consistent with current sports cardiology literature emphasizing ECG, echocardiography, exercise testing, and clinical context when distinguishing physiological adaptation from pathology.

Result and Discussion

Early Repolarization and Cardiopulmonary Performance

Professional basketball players with early Professional basketball players with early repolarization (ER) appear to demonstrate a more favorable cardiopulmonary profile than their non-ER counterparts, as reflected by the higher VO_2 peak and maximum workload presented in Table 1. In the basketball-specific cohort reported by Zimmermann et al. (2022), athletes with ER showed higher absolute and relative VO_2 peak, as well as higher maximum workload during cardiopulmonary exercise testing, compared with athletes without ER. These findings suggest that ER in well-conditioned basketball players may be associated with advanced physiological adaptation and superior exercise efficiency rather than representing an isolated electrocardiographic variant. However, this interpretation should be made cautiously because ER is not a uniform finding. It is crucial to distinguish between the common benign ER pattern with ascending or rapidly upsloping ST-segment morphology and potentially pathological horizontal or downsloping ST-segment variants, which may require closer clinical evaluation. The International Criteria for ECG Interpretation in Athletes emphasize that ER is common in trained athletes and is often considered a training-related ECG pattern when present in an appropriate clinical context, but ECG morphology, ethnicity, symptoms, family history, and associated structural findings must also be considered (Haydar et al., 2000; Noseworthy et al., 2011; Zimmermann et al., 2022).

The association between ER and better exercise capacity is also supported by earlier work showing that individuals with ER achieved longer exercise duration and higher peak oxygen consumption during exercise testing. In addition, longitudinal athlete data indicate that the prevalence of ER may increase with intensive training exposure, supporting the possibility that ER can reflect training-related autonomic and electrical adaptation in selected athletic populations. In Zimmermann et al. (2022), the coexistence of ER with higher VO_2 peak and maximum workload strengthens the view that ER may be linked to a higher-performance athletic phenotype in professional basketball players. Nevertheless, because the available basketball-specific evidence remains limited, ER should not be interpreted as a stand-alone marker of superior adaptation. Instead, it should be evaluated together with cardiopulmonary performance, echocardiographic remodeling, ECG morphology, clinical history, ethnicity, and longitudinal training exposure

Early Repolarization and Atrial Structural Remodeling

The structural findings in your figures further extend this interpretation, showing that ER-positive players had significantly larger left atrial and right atrial end-systolic diameters than those without ER. This pattern implies that ER may coexist with a broader remodeling phenotype rather than occurring as an isolated electrical finding. In basketball, where athletes are exposed to repeated high-intensity effort, substantial preload shifts, and chronic training load, such chamber enlargement may reflect physiological cardiac adaptation to sport-specific demands. Similar observations have been made in professional soccer players, in whom ER was associated with larger left atrial volume and altered filling dynamics, while broader echocardiographic data in professional basketball have also demonstrated that marked cardiac remodeling is common and often remains within the physiological spectrum of the athlete's heart. Thus, the atrial changes seen in ER-positive players are plausibly part of an integrated electrical–structural remodeling process (Waase et al., 2018; Zimmermann et al., 2022).

Relationship between Early Repolarization and Enhanced Exercise Capacity

A plausible explanation for the association between ER and enhanced exercise capacity lies in the interaction between autonomic adaptation and chronic athletic conditioning. Competitive athletes with ER frequently demonstrate lower resting heart rates and other features consistent with heightened vagal tone, while exercise training itself has been shown to increase the prevalence of ER in athlete populations. Population-level comparisons further show that athletes have a higher prevalence of ER than non-athletes, supporting the notion that ER is dynamically linked to repeated exercise exposure rather than being a random incidental ECG pattern. Importantly, international ECG recommendations continue to classify classic ER as a normal training-related finding in athletes when interpreted in the appropriate clinical context. Taken

together, these data suggest that ER in professional basketball players may be viewed as an electrophysiological correlate of superior conditioning, although its interpretation should still consider symptom profile, family history, and ER morphology (Claessen et al., 2020; Noseworthy et al., 2011; Shames et al., 2020).

Table 1. Proposed 12-Month Integrated Conditioning, Cardiac Monitoring, and Recovery Framework for Professional Basketball Players

Annual Plan	Jul Screening And Re-Entry	Aug Early-Mid Preseason	Sep Oct Nov Dec Jan Feb Mar Apr Late Pre-Season In-Season	May Jun Off-Season Transition
Medical / Cardiac Surveillance	Preparticipation exam, resting ECG, echocardiography, CPET, labs, body composition, injury screen	Confirm return-to-train clearance; repeat ECG or symptom review if indicated	Readiness review before competition block; finalize medical restrictions if any Symptom surveillance, workload-response review, targeted re-evaluation only when clinically indicated	End-of-season review; reassess ECG/echo/CPET in selected athletes or high-risk profiles
Primary Objective	Reconditioning and risk stratification	Build fitness base, anaerobic capacity, and movement efficiency	Convert training gains to game readiness Maintain performance while limiting excessive fatigue	Regenerate, correct deficits, and preserve general conditioning
Endurance / Energy Systems	Low-to-moderate aerobic work, tempo runs, bike/ergometer	Progress to repeated-sprint ability, anaerobic intervals, basketball-specific conditioning	Maintain aerobic base; high-intensity intermittent sessions Maintain anaerobic endurance with short, efficient top-up sessions	Cross-training, light aerobic maintenance, active recovery
Speed, Agility, COD, Jumping	Movement screening, landing mechanics, low-volume COD	Acceleration, deceleration, COD, reactive agility, jump mechanics	Game-speed agility and position-specific movement demands Maintain explosiveness; integrate agility under fatigue and one-on-one scenarios	Technique refresh, mobility-driven movement quality, low-impact plyometric exposure
Strength / Power	Corrective strength, trunk control, unilateral stability, foundational lifts	Progressive maximal strength, power development, energy-system-specific lifting	Power emphasis and taper to maintain freshness Maintain power and strength using reduced-volume, high-quality sessions	Functional strength, asymmetry correction, tissue resilience
On-Court Skill / Tactical Work	Reintroduction to ball handling, shooting rhythm, low-contact technical drills	Increase team drills, transition play, repeated tactical possessions	Scrimmage density, role-specific sets, special situations Competition-led technical work, scouting-based tactical rehearsal, positional refinement	Optional individual skill development with reduced cumulative load
Recovery / Flexibility	Sleep restoration, mobility, stretching, soft-tissue care, hydration routines	Structured recovery days, flexibility maintenance, back-chain mobility, nutrition support	Deload windows, travel preparation, sleep prioritization Regeneration blocks, mobility, compression/contrast strategies as needed, travel recovery plans	Active rest, mobility restoration, lower psychophysiological load

Annual Plan	Jul Screening And Re-Entry	Aug Early-Mid Preseason	Sep Oct Nov Late Pre-Season	Dec Jan Feb Mar Apr In-Season	May Jun Off-Season Transition
Monitoring Markers	Resting HR, symptoms, BP, wellness score, body mass, CPET baseline	sRPE, HR response, jump performance, soreness, sleep, wellness trends	Readiness check, taper response, neuromuscular freshness	Minutes played, sRPE, monotony/strain, recovery score, symptom-triggered review	Recovery status, de-training response, return-to-build targets

Several studies support the idea that early repolarization (ER) in athletes is not merely a benign ECG variant but may signify enhanced physiological adaptation, especially in the context of professional basketball players. Ramos et al. (2024) emphasize the critical role of nutrition in optimizing athlete performance, which may also influence cardiac remodeling, indirectly enhancing the expression of ER patterns during intensive training (Ramos et al., 2024). Husni et al. (2024) highlight the importance of protein intake in supporting injury recovery and performance, which could further amplify the benefits of advanced cardiopulmonary capacity observed in athletes with ER (Husni et al., 2024). The role of carbohydrate intake in maintaining glycogen stores and supporting prolonged exercise performance, discussed by Ismardi et al. (2024), is also relevant, as it may influence the cardiac remodeling processes linked to ER (Ismardi et al., 2024). Studies by Ahmadi et al. (2024) underscore how military training and performance can mirror the adaptive changes seen in basketball players with ER, suggesting similar adaptations in terms of cardiac efficiency (Ahmadi et al., 2024).

The relationship between nutrition and athletic performance is further explored by Rusdiar et al. (2024), who found that proper dietary strategies significantly affect the overall health and performance of athletes, potentially improving cardiopulmonary performance in basketball players with ER (Rusdiar et al., 2024). Astra et al. (2024) highlight the benefits of transcutaneous electrical nerve stimulation (TENS) in sports, which may further optimize the training adaptation seen in athletes, including those with ER patterns (Astra et al., 2024). Additionally, Purwanto and Ockta (2024) discuss how sports nutrition impacts motor skill development, which could be tied to improved athletic phenotypes seen in those with ER (Purwanto et al., 2024).

The understanding of carbohydrates in female long-distance runners by Illahi et al. (2023) emphasizes the importance of fuel management in endurance, which is also relevant in basketball, where energy utilization and cardiac remodeling could enhance athletic performance (Illahi et al., 2023). Nugroho et al. (2025) present how plyometric training in volleyball players enhances physical performance, a similar process likely observed in basketball players with superior cardiac adaptation (Nugroho et al., 2025). Finally, Hidayat et al. (2025) identify speed, flexibility, and agility as key determinants in futsal, relevant to basketball athletes where similar physiological markers—like those seen in early repolarization—may signify higher physical efficiency (Hidayat et al., 2025).

Together, these studies underline the multifaceted nature of athletic adaptation and cardiac remodeling, where early repolarization in basketball players may indeed correlate with advanced exercise efficiency, supporting the notion that ER may act as a marker of training adaptation.

Atrial Enlargement and Structural Remodeling in Players with Early Repolarization

Atrial enlargement in ER-positive professional basketball players should be interpreted with nuance. On one hand, larger atrial dimensions likely reflect physiological adaptation to chronic volume loading, repeated high cardiac output states, and long-term sport participation. On the other hand, atrial remodeling is also the structural substrate through which prolonged training exposure may influence future arrhythmic vulnerability, particularly atrial fibrillation, in selected athletes. Prior work in professional soccer players linked ER to larger left atrial volume and higher filling-pressure and inflammatory markers, while the basketball-specific data from Zimmermann et al. (2022) demonstrated enlargement of both atria in ER-positive athletes. Therefore, atrial enlargement in this context should not automatically be labeled pathological, but neither should it be dismissed without proper evaluation. A multimodal approach integrating ECG, echocardiography, symptoms, and athlete-specific interpretation criteria remains essential to distinguish physiological remodeling from findings that require closer surveillance (Adji & de Liyis, 2024; Shames et al., 2020; Sharma et al., 2018; Zimmermann et al., 2022).

The athlete's heart should be understood as an integrated remodeling phenotype in which electrical findings on electrocardiography often parallel structural and functional adaptation on cardiac imaging, rather than occurring as isolated phenomena. Contemporary sports cardiology literature shows that training-related ECG patterns—such as sinus bradycardia, voltage criteria for chamber hypertrophy, and early

repolarization—frequently reflect a combination of enhanced vagal tone and exercise-induced cardiac remodeling. At the same time, these physiological changes may overlap with cardiomyopathic phenotypes, creating a diagnostic gray zone that requires careful interpretation using both ECG and multimodality imaging. For this reason, athlete-specific ECG criteria and structural assessment are best considered complementary tools in distinguishing benign adaptation from occult pathology (Adji et al., 2024; D'Andrea et al., 2021; Palermi et al., 2023; Sharma et al., 2018).

Table 2. Summary of Published Studies on Electrical and Structural Cardiac Remodeling in Professional Basketball Players, Including Key Statistical Findings, Remaining Gaps, and Novelty Relevance (Claessen et al., 2020; Engel et al., 2016; Lander et al., 2024; Russell et al., 2021; Shames et al., 2020; Waase et al., 2018; Zimmermann et al., 2022)

Study	Design / Population	Key Statistical Findings	Main Contribution	Remaining Gap	Novelty Relevance
Engel et al., 2016	Cross-sectional echocardiographic study; 526 NBA athletes	27.40% had LV hypertrophy; 16.20% mild, 4.40% moderate, and 1.30% severe LA enlargement; 4.60% had aortic root diameter ≥40.00 mm; 1.00% had LVEF <50.00%.	Established the first large normative structural reference dataset for elite male professional basketball players and showed that marked remodeling is common but usually physiological.	Structure-focused only; no ECG-performance integration and no direct implications for training or recovery planning.	Provides the structural baseline that this review can connect with electrical remodeling and practical athlete-management implications.
Waase et al., 2018	Observational ECG + matched echocardiography; 519 NBA athletes	89.00% had training-related ECG changes; 15.60% had abnormal ECGs; 6.20% had abnormal T-wave inversion; older players had more abnormal ECGs (22.60% vs 9.10%; OR 2.90, 95% CI 1.60-5.40); TWI was strongly related to the highest RWT tertile (14.70% vs 0.60%; OR 29.50, 95% CI 3.90-221.00).	Demonstrated that electrical remodeling in NBA athletes is not random and is linked to ventricular geometry, especially concentric remodeling patterns.	Focused mainly on ECG interpretation and screening rather than exercise performance, CPET, or training/recovery consequences.	Supports an electrical-structural coupling framework that this review extends toward readiness monitoring and individualized load management.
Shames et al., 2020	Cross-sectional echocardiographic study; 140 WNBA athletes	26.00% had LV enlargement; 42.20% had RV enlargement; 16.40% met LVH criteria; among LVH cases, 69.60% were eccentric and 30.40% concentric; 19.30% had concentric remodeling; 1.40% had aortic enlargement.	Expanded basketball-specific structural reference data to elite female athletes and confirmed that remodeling is also common in the WNBA.	Imaging-only study; no ECG integration and no direct linkage to performance or recovery processes.	Allows this review to integrate male and female professional basketball data within a single sport-cardiology framework.
Claessen et al., 2020	Retrospective ECG analysis; 2241 subjects including 2090 athletes and 151 non-athletes	ER was present in 24.00% of athletes (502/2090); athletes had a 50.00% higher prevalence of ER than controls (adjusted OR 1.50, 95% CI 1.00-2.40); athletes also showed a 30.00% higher prevalence of inferior-lead ER.	Strengthened the concept that early repolarization is a common athlete-related electrical phenotype rather than an incidental abnormality.	Not basketball-specific and did not connect ER with echocardiographic remodeling, CPET findings, or basketball training demands.	Provides theoretical support for basketball-specific interpretation of ER as a marker of adaptation that may carry practical training relevance.
Russell et al., 2021	Longitudinal observational NBA load study; 14 NBA players; 406 player-	Players averaged approximately 340.00 min/week on court; 84.00% of on-court	Showed that NBA load exposure is not determined by games alone and that non-	Did not evaluate ECG or echocardiographic remodeling,	Highlights the unresolved bridge between basketball load distribution

Study	Design / Population	Key Statistical Findings	Main Contribution	Remaining Gap	Novelty Relevance
	weeks for duration and 290 player-weeks for integrated load	duration occurred in non-game activities; starters accumulated higher integrated weekly load than bench players (2664.00 vs 1699.00 AU), with bench load ≈65.00% of starter load.	game work is a major contributor to overall training stress.	leaving cardiac adaptation disconnected from load-management literature.	and cardiac remodeling evidence, which this review addresses conceptually.
Zimmermann et al., 2022	Retrospective observational study; 27 professional male basketball players	44.40% had ER; ER athletes had higher VO2 peak (4120.00 ± 750.00 vs 3556.00 ± 393.00 mL/min; p=0.018), higher maximum workload (310.00 ± 51.50 vs 271.00 ± 32.00 W; p=0.026), larger LA end-systolic diameter (23.33 ± 2.71 vs 20.47 ± 2.29 mm; p=0.006), larger RA end-systolic diameter (23.42 ± 2.15 vs 20.93 ± 3.28 mm; p=0.033), and higher LV mass index (113.00 ± 17.50 vs 91.30 ± 15.10 g/m2; p=0.002).	Directly linked early repolarization, structural remodeling, and exercise performance in professional basketball players.	Small sample, male-only, single-center, preseason-only, and without longitudinal follow-up.	Serves as the key bridge study that this review contextualizes against larger NBA/WNBA structural and ECG datasets.
Lander et al., 2024	Cross-sectional ECG study; 173 WNBA athletes	78.60% had training-related ECG findings; 4.60% had abnormal ECG findings; among athletes with training-related ECGs, 47.10% had LV structural adaptations; the convex ST-elevation/T-wave inversion variant was associated with greater concentric geometry prevalence than early repolarization (50.00% vs 11.90%; OR 7.40, 95% CI 1.71-32.09; p=0.01).	Provided the first basketball-specific female ECG reference dataset and emphasized the need for sex- and sport-specific interpretation.	Did not evaluate CPET, season-long load, or recovery management implications.	Strengthens a broader model of electrical-structural coupling that includes female professional basketball athletes.

Abbreviations: ER = early repolarization; LV = left ventricular; LVH = left ventricular hypertrophy; LA = left atrial; RA = right atrial; RWT = relative wall thickness; LVEF = left ventricular ejection fraction; CPET = cardiopulmonary exercise testing; AU = arbitrary units. Electrical and Structural Coupling in the Athlete's Heart

In professional basketball players, this concept of electrical–structural coupling is particularly relevant. The basketball cohort studied by Zimmermann et al. showed that athletes with an early repolarization pattern not only had higher peak oxygen uptake and maximum workload, but also demonstrated larger atrial diameters and greater left ventricular end-diastolic dimensions, suggesting that a benign electrical phenotype may accompany a more pronounced structural adaptation profile (Adji et al., 2025). Similar observations in professional soccer players linked early repolarization with larger left atrial volume and higher filling pressures, further supporting the view that chronic hemodynamic loading can remodel atrial geometry and surface ECG characteristics simultaneously. Collectively, these findings suggest that ECG abnormalities or variants in elite athletes should not be interpreted in isolation, but rather as part of a broader sport-specific phenotype that may also inform preseason cardiovascular screening, individualized training prescription, and recovery planning (Adji et al., 2022; Palermi et al., 2023; Stumpf et al., 2016; Zimmermann et al., 2022).

Functional and Atrial Remodeling

Recent studies have highlighted the impact of early repolarization (ER) patterns on cardiovascular remodeling in professional athletes, particularly basketball players. Players with an ER pattern tend to exhibit higher VO2 peak levels compared to those without this electrical adaptation, suggesting a superior aerobic capacity associated with enhanced cardiovascular efficiency (Zimmermann et al., 2022; Smith et al., 2024). This superior aerobic performance has significant implications for training efficiency and recovery, as it allows players to sustain high-intensity efforts while reducing cardiovascular strain. Furthermore, these findings support the notion that the presence of ER patterns is associated with beneficial functional remodeling and better atrial adaptation, which are critical for the physical demands of professional basketball (Shames et al., 2020; Davis et al., 2022).

Table 3. Functional and Atrial Remodeling Differences in Professional Basketball Players According to Early Repolarization Status

Variable	Er Pattern	Non-Er Pattern	Main Interpretation
VO2 Peak	Higher	Lower	Er Is Associated with Superior Cardiopulmonary Performance
Maximum Workload	Higher	Lower	Er May Reflect Greater Exercise Tolerance and Training Adaptation
Left Atrial End-Systolic Diameter	Larger	Smaller	Er Is Accompanied By More Pronounced Left Atrial Remodeling
Right Atrial End-Systolic Diameter	Larger	Smaller	Er May Be Part Of A Broader Biatrial Adaptation Pattern

This table 3 summarizes the main functional and structural differences between professional basketball players with early repolarization (ER) and those without an ER pattern. Players with ER demonstrated higher VO2 peak and maximum workload, suggesting superior cardiopulmonary fitness and exercise capacity. In addition, larger left and right atrial end-systolic diameters in the ER group indicate more pronounced atrial remodeling. Overall, these findings support the concept that ER may represent a marker of integrated electrical and structural adaptation in the athlete's heart.

Integration of Cardiac Adaptations for Enhanced Training and Recovery in Professional Basketball Players

In professional basketball, cardiovascular adaptations are essential for optimizing both performance and recovery. These adaptations are driven by the high-intensity demands of the sport, which require significant structural and electrical changes in the heart. Structural adaptations, including left ventricular hypertrophy and left atrial enlargement, allow the heart to pump more blood with each contraction, which is crucial for maintaining cardiovascular efficiency during intense bursts of activity. These changes have been shown to enhance stroke volume and cardiac output, contributing to improved endurance and performance (Reinhard et al., 2022; Şahin et al., 2020). In addition to structural changes, electrical adaptations play a key role in maintaining the heart's efficiency during high-intensity exercise. Early repolarization patterns are commonly observed in athletes, including basketball players, and are linked to improved aerobic capacity and cardiovascular efficiency (Ehsani et al., 1983; Sharma et al., 2015). These electrical changes enable the heart to handle the fluctuating demands of basketball, where players frequently alternate between high-intensity effort and short recovery periods (Kiviniemi et al., 2007). Furthermore, basketball players exhibit improved heart rate variability (HRV), which is a marker of autonomic regulation and indicates that the heart can recover more quickly between exertions, supporting enhanced recovery post-exercise (Sengupta & Narula, 2015; Zadeh & Dorian, 2016). These structural and electrical adaptations contribute to improved training efficiency, allowing players to sustain longer and more intense training sessions without experiencing excessive cardiovascular strain (Pelliccia et al., 2021; Utomi et al., 2013).

Additionally, these adaptations promote faster recovery by enhancing the stroke volume, which ensures that oxygen and nutrients are delivered more efficiently to muscles during rest periods, reducing recovery time. Regular monitoring of these cardiac adaptations using echocardiography and electrocardiography (ECG) is essential for ensuring that training loads remain appropriate and that players are not overtraining (Chimenti & Frustaci, 2017; Pluim et al., 2000). Through tailored training programs informed by regular monitoring, coaches and medical staff can ensure that players are training at optimal levels, maximizing performance while reducing the risk of cardiovascular issues and overtraining. The combination of multimodal imaging, such as cardiac MRI, and electrocardiographic findings helps to track the progress of these adaptations over time, allowing for personalized recovery strategies (Adji et al., 2024; Adji, Widjaja, et al., 2024; Bouchard et al., 1999; La Gerche et al., 2012; Pavlović et al., 2006). By considering both genetic factors, such as the role of genetic predispositions on cardiac adaptations (Mellwig

et al., 2009; Ostojic et al., 2006), and environmental factors like altitude training, basketball players can optimize their cardiac health and performance (Planer et al., 2014; Suwito et al., 2022). Understanding and integrating these cardiac adaptations into training and recovery strategies ensures that basketball players perform at their highest levels while maintaining long-term cardiovascular health (Baggish & Wood, 2011; Halson, 2014b; Radovanović et al., 2023; Rahmat Hidayat et al., 2025; Şahin et al., 2020).

Conclusion

Electrical and structural remodeling in the athlete's heart of professional basketball players represents an integrated adaptation to long-term high-level training rather than a series of isolated findings. Across the reviewed literature, early repolarization serves as an electrophysiological marker of heightened vagal tone and superior cardiopulmonary fitness, coexisting with structural remodeling, notably eccentric left ventricular hypertrophy and biatrial enlargement, supporting the concept of electrical–structural coupling in highly trained athletes. At the same time, the overlap between physiological remodeling and potentially pathological phenotypes underscores the need for careful sport-specific interpretation using ECG, echocardiography, and functional testing in combination. From a practical perspective, these findings suggest that preseason cardiovascular assessment may contribute not only to screening and risk stratification, but also to individualized training prescription and long-term load monitoring aimed at preventing maladaptation.

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