

Hemodynamic modeling of aerobic adaptation in football players through interval-functional training

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Abstract.

Problem Statement. With increasing demands on the functional fitness of young football players during dynamic, intermittent competitive activities, developing biologically based training protocols that promote an energy-efficient and hemodynamically stable circulation system is particularly important. Traditional basic training methods show limited effectiveness in stimulating the central and peripheral mechanisms responsible for aerobic capacity, highlighting the need to shift towards integrative models of physiological adaptation. **Approach.** This study uses the concept of targeted hemodynamic modeling through a multi-component aerobic adaptation program (PHDA). The program includes interval-functional running, partial vascular occlusion (BFR) techniques and neurorespiratory and vegetative-regulatory practices. The experimental intervention (n=22) spanned two mesocycles (8 weeks) and was compared with a control group (n=22) following the standard Youth Sports School training protocol. The diagnostic tools included chest rheography, PWC170, calculation of $\dot{V}O_2$ max, heart rate (HR) and heart rate variability (HRV) indices. **Purpose.** The scientific verification of the effectiveness of PHDA in increasing the parameters of central hemodynamics and aerobic performance of football players aged 13–15 years at the stage of preliminary sports specialization. **Results.** In the experimental group, statistically significant changes ($p < 0.05$ – 0.001) were recorded: the increase of stroke volume ($\uparrow 18.2\%$), left ventricular power output ($\uparrow 40.3\%$), $\dot{V}O_2$ max ($\uparrow 9.93\%$), cardiac index and PWC170 indicators in absolute and relative values. The improvement of autonomic regulation ($\downarrow$ resting heart rate, $\uparrow$ HRV) and the reduction of total peripheral vascular resistance were observed, with simultaneous increase of systemic cardiac output. The control group demonstrated inertia of physiological parameters. **Conclusions.** The PHDA program induces a complex functional restructuring of the cardio-hemodynamic profile, forming a hyperkinetic, energy-efficient and vegetatively balanced type of blood circulation, adequate to the game metabolic loads. The presented data indicate the high potential of physiologically integrated protocols as a tool for accelerated development of aerobic endurance and adaptive reserve of young athletes.

Key words: football players, stage of preliminary basic training, central hemodynamics, aerobic productivity, hyperkinetic type of blood circulation, physiological adaptation.

Introduction

Modern football is characterized by a high density of competitive activity, a pronounced predominance of a variable intensity of game rhythm and the need for rapid neurovegetative restoration, improving the functional fitness of athletes at the early stages of sports specialization is of particular relevance (Malikov et al., 2021; Rodrigues et al., 2023). Adolescence (13–15 years) is a crucial sensitive period during which fundamental adaptive mechanisms of the cardiovascular and respiratory systems are laid down, determining the potential capabilities of a football player at the stages of subsequent specialization (Tyshchenko et al., 2025; Weston et al., 2014). However, traditional means of training, applied at the stage of preliminary basic training, as a rule, do not provide sufficient stimulation of the central mechanisms of hemodynamics and aerobic productivity, being limited mainly to a general developmental and technically-oriented approach.

Modern scientific data indicate the need to shift from mechanistic training models to targeted structural and functional modeling of physiological adaptation, including work with stroke volume, cardiac index, left ventricular power, minute blood volume and oxygen utilization (Malikov et al., 2019; McMillan et al., 2005; Read et al., 2006). At the same time, the influence of interval-functional training programs with the elements of BFR (partial occlusion) on the physiological indices of blood circulation and oxygen utilization of adolescent football players remains underexplored. Thus, there is an objective scientific and practical need to substantiate and experimentally test the effectiveness of modern training models aimed at adaptive cardiac hemodynamic development of young football players, taking into account age characteristics, the specifics of competitive activity and the requirements for the functional stability of the cardiovascular system.

The aim of this research is scientific substantiation and experimental verification of the effectiveness of a specialized training program using hemodynamic aerobic adaptation (PHDA) for improving the functional indicators of central hemodynamics and aerobic productivity in young football players at the stage of preliminary basic training.

Materials and methods.

Participants. The participants of this study are two hundred football players aged 13-15 of Ukrainian Children's Youth Sports School (UCYSS) at the pre-basic training stage (age = 13-15 years). The experimental group used the author's program of hemodynamic aerobic adaptation (PHDA), including interval, occlusion and respiratory effects, and the control group used the standard UCYSS program.

All athletes volunteered to participate in this research. Prior to the testing, the procedures were explained to all of them, including possible risks involvement, and, after the explanation, an informed consent form was signed. The athletes were free from any injuries or neuromuscular disorders.

The research was approved by the Institutional Ethics Committee, complied with all relevant national regulations and institutional policies, followed the tenets of the Declaration of Helsinki, and has been approved by the authors' institutional review committee. Exclusion criteria were a history of injury or disease that would prevent participants from safely performing the research protocol.

Research Methods

Theoretical methods: theoretical analysis and generalization of scientific and methodological literature; systematization and interpretation of empirical data; modeling of the content of training impact.

Practical methods: pedagogical observation of the educational and training process; pedagogical experiment (formative experiment with control and experimental groups).

Physiological and biomedical methods: chest rheography – to assess central hemodynamic parameters (stroke volume (SV), minute blood volume (MBV), cardiac index (CI), left ventricular power (LVP), total peripheral resistance (TPR)); functional test PWC_{170} – to assess the overall physical performance and adaptive potential of the heart; calculation of the relative PWC_{170} indicator (W/kg) and the maximum rate of oxygen consumption (VO_{2max}) using standard formulas for age and body weight; monitoring of heart rate (HR) at rest and after a load – as an indicator of autonomic regulation and functional readiness of the cardiovascular system.

Data collection and analysis / Statistical analysis: calculation of the arithmetic mean, standard deviation, and error of the mean; determination of the reliability of differences using the Student's criterion (t-criterion) for dependent and independent samples; analysis of relative changes ($\Delta\%$) between the initial and control measurements. The methodological basis of the PHDA was based on three key components: interval-periodic training with a variable pace (IPT), aimed at stimulating the cardiac index (CI) and increasing the functional reserve of the myocardium due to the alternation of phases of intensive and recovery running. Control is carried out according to the PWC_{170} indicator, which allows to individualize the load depending on the current adaptation state; aerobic intervals of submaximal intensity (70–80% HRmax) to develop maximum oxygen consumption (VO_{2max}), capillary network and mitochondrial biogenesis in working muscle groups, which contributes to boost oxidative metabolism and to increase overall endurance without acidification; functional circuit training with elements of BFR (partial occlusion), used for targeted increase of SV and LVP without excessive load on the myocardium by activating the Frank-Starling mechanism and physiological hypertrophy without increasing systemic pressure.

The targeted effect of PHDA spanned 8 weeks and included two mesocycles of 4 weeks each, which provided both the phase of load and the adaptive compensatory processes. The implementation of the training program has ensured the activation of a number of central and peripheral physiological mechanisms that determine the functional adaptation of the cardiovascular system of adolescents aged 13–15 years:

1. Strengthening the pumping function of the heart ($\uparrow$ SV, $\uparrow$ LVP). Due to submaximal interval loads and occlusion stimulation (BFR), there is an increase of preload and extensibility of the walls of the left ventricle, activation of the Frank-Starling mechanism, an increase in the amplitude of systolic ejection, and morphofunctional strengthening of the heart muscle (physiological hypertrophy). As a result, the heart works more powerfully and economically, with a smaller number of contractions, a greater blood output is achieved – the key to increase SV and LVP.

2. Increase of minute blood volume ($\uparrow$ MBV, $\uparrow$ CI). Interval running loads in the range of 70–85% HRmax stimulate the intensification of venous return, the increase of diastolic filling, the adaptation of the heart rate to the working rhythm with less sympathetic activation, and the formation of a hyperkinetic type of blood circulation. Due to this, the heart transports more blood per unit of time, and with it – oxygen, which improves the functional capacity of the body under the conditions of variable load (typical for football).

3. Development of oxygen potential ($\uparrow$ VO_{2max}). Systematic aerobic intervals and respiratory elements (inhalation-exhalation under a load, breath holding) stimulate the growth of mitochondrial density, the increase of the capillary network in active muscles, the raise in the activity of oxidative enzymes (TCA, ETC), and improvement of oxygen utilization in the periphery. The effect is to improve the ability of muscles to extract and use oxygen during prolonged or repeated work – a key marker of aerobic endurance in football.

4. Optimization of vascular regulation ($\downarrow$ OVR). Against the background of increased minute blood volume and periodic phases of muscle relaxation, activation of endothelial vasodilation (release of NO), a decrease of the tone of peripheral arterioles, improvement of vascular compliance, and the formation of a more stable and economical vascular resistance occur. The resulting reduction of TPR allows the body to cope better with increased cardiac output without pressure overload, reducing cardiac expenditure.

5. Improvement of autonomic regulation and recovery mechanisms ($\uparrow$ HRV, $\downarrow$ Heart Rate at Rest). The inclusion of neurorespiratory yoga, heart rate control phases and breath holding enhances parasympathetic activity, vagal tone, baroreflex arc adaptation, recovery after loads and transition to a state of rest. Due to this, the heart recovers faster among game situations, works more stably under load and is less susceptible to overload.

The hemodynamic aerobic adaptation program (PHDA) takes into account the scientific and physiological foundations: conditioning interval sprint training (CIST); Intermittent Hypoxic Interval Training (IHIT); BFR (occlusion load) to increase SV at low heart rate; neurohemodynamic restructuring model (NGT): a combination of respiratory holds, coordination and submaximal muscle activation (Tables 1, 2).

Table 1. Program of hemodynamic aerobic adaptation (PHDA) for a week (4 training days)

Day	Focus	Content	Targeted effect
Mon	Central hemodynamics	Interval running 3×5 min (75–80% HRmax) + BFR load (squat + step-up + plank)	$\uparrow$ SV, $\uparrow$ LVP, increase cardiac output
Tue	Microcirculation + breathing	Sprints 20/20×12 + walking with breath holding + lateral movements in hypoxic conditions	$\uparrow$ VO ₂ max, $\downarrow$ TPR, increase of oxygen buffer
Wed	Autonomous regulation	Dynamic Neuro-Yoga + Cardiovascular myostability Exercises (isometry + slow breathing + HRV control)	$\downarrow$ HR, $\uparrow$ HRV, increase of stability at rest
Thu	Hemodynamic overload	Mini-games 3×12 min + functional circuits (TRX, medball, platform jumps) with real-time heart rate tracking	$\uparrow$ CI, $\uparrow$ tolerance to "spurt-recovery" cycles

Specific methods within the PHDA included: "Step-Torque Jump" – plyometrics on a box under BFR cuffs; "Recovery Hold-Breathe" – holding the breath on exhalation between series; "Cardio Chess Drill" – micro series "attack-pause-counterattack" with heart rate monitoring; "RBC booster sets" – functional running + hypoxia (analogous to natural stimulation of erythropoietin production).

Table 2. Mechanisms – stimuli – results – football effects

Physiological mechanism	Training stimulus	Physiological result	Football effect
Increasing of SV and LVP	Interval loads + BFR + PLYO-load	Increasing of systolic function and preload	Reducing of fatigue during a series of spurts, maintaining in accuracy of passes and shots
Growth of MBV and CI	Running intervals 70-85% HRmax + game series	Increasing of circulating blood volume at a stable heart rate	Stable capacity during the 2nd half, resistance to hypoxia
Increasing of VO ₂ max	Submaximal aerobic intervals + breath holding	Development of mitochondrial density and capillarization	Improvement of speed endurance and intensity of repeated actions
Reduction of TPR	Alternating phases of tension and relaxation in circuit exercises	Improvement of vascular compliance and reduction of vascular tone	More economical distribution of oxygen, less acidification in muscles
Improvement of autonomic regulation and recovery (HRV, HR)	Neuro-yoga, breathing practices, HR control	Activation of parasympathetic regulation, accelerated recovery	Fast recovery between game episodes, fewer rhythm breakdowns

Results.

At the formation stage of the pedagogical study, the features of changes of the functional state of the cardiovascular system according to the parameters of chest rheography, as well as physical performance of football players at the stage of preliminary basic training were identified (Table 3). The results of the dynamic analysis of the changes in the PWC₁₇₀ and maximum oxygen consumption (VO₂ max) make it possible to improve significantly the functional state of the cardiorespiratory system of the football players in the

experimental group under the influence of targeted PHDA. A fixed increase of PWC_{170} by 112.00 kgm/min ($p<0.001$) indicates a pronounced adaptive restructuring of central hemodynamics. The increase of power at submaximal load (HR 170 bpm) is interpreted as a result of the increase in stroke and minute volume of the heart, which directly indicates the improvement of myocardial function. Certain changes are characteristic of the phenomenon of "sports hyperfunction of the heart", when, as a result of systematic training load, morphofunctional adaptation of the cardiovascular system to an increased volume of work occurs. At the same time, the increase of the ejection fraction, the improvement of the functional reserve of the heart and the efficiency of hemocirculation are noted.

Table 3. Changes in the functional state indicators of football players of both groups at the stage of preliminary basic training at the formation stage of the study

Indicator, unit of measurement.		Experimental group (n=22)			Control group (n=22)		
		before	after	p	before	after	p
PWC_{170} , kgm/min		520,48±8,77	632,48±8,75***	<0,001	522,77±9,65	545,36±8,49	>0,05
PWC_{170} , kgm/min/kg		11,56±1,33	14,03±1,17*	<0,05	11,78±1,47	12,02±1,15	>0,05
VO_2 max, ml/min/kg		50,45±1,55	55,45±1,13*	<0,05	50,98±1,66	51,03±1,33	>0,05
SV, ml	fact.	54,47±1,55	64,39±1,12**	<0,001	55,41±1,56	57,63±1,32	>0,05
	% of predicted	87,66±1,98	98,37±1,77**	<0,001	87,59±1,99	88,99±1,27	>0,05
MBV, l/min		3,58±0,18	4,15±0,20**	<0,001	3,59±0,19	3,62±0,21	>0,05
CI, l/min·m ²		2,18±0,08	2,43±0,10**	<0,001	2,19±0,09	2,23±0,10	>0,05
TPR dyn·s/cm ⁵	fact.	1802,2±24,6	1796,7±41,4	>0,05	1805,2±23,4	1800,0±42,4	>0,05
	% of predicted	98,99±1,74	96,55±1,85	>0,05	98,94±1,79	97,92±3,12	>0,05
LVP W	fact.	2,01±0,09	2,82±0,10***	<0,001	2,02 ±0,07	2,12±0,11	>0,05
	% of due predicted	78,39±1,91	87,54±1,51***	<0,001	78,34±1,92	81,92±1,54	>0,05

Note: * – $p<0.05$; ** – $p<0.01$; *** – $p<0.001$ comparing the final indicators of the experimental and control groups of football players

In the control group, the increase in PWC_{170} by 22.59 kgm/min did not acquire statistical significance ($p>0.05$), which indicates insufficient stimulation of the mechanisms of chronic cardio-hemodynamic adaptation under the conditions of traditional training load. The increase in this indicator in the experimental group by 2.47 kgm/min/kg ($p<0.05$) confirms that the efficiency of the cardiovascular system increased not only in absolute values, but also relative to the body weight of the athletes, which is more informative for the analysis of sports endurance. Such dynamics shows the improvement of the specific volume of blood flow and oxygen transport, that is, it reflects the harmonization of the functional mass of the myocardium and the somatic mass of the athlete. Minor changes in the control group (+0.24 kgm/min/kg, $p>0.05$) indicate a limited effect of standard training methods on the relative functional capacity of the cardiovascular system.

The increase in the VO_2 max by 5.00 ml/min/kg ($p<0.05$), which corresponds to the growth of 9.93%, indicates an intensification of oxygen metabolism and the aerobic energy system. This is due to both central mechanisms (increasing of cardiac output and oxygen transport) and peripheral adaptations, in particular, increasing of mitochondrial biogenesis in muscle cells; increasing of capillary density and oxygen diffusion area; increasing of oxidative activity of TCA cycle (Tricarboxylic Acid Cycle) enzymes. This is especially relevant for football players, as improved aerobic endurance is associated with increased activity of TCA cycle enzymes TCA cycle – such as citrate synthase, isocitrate dehydrogenase, and other mitochondrial dehydrogenases – which enhance oxygen utilization and delay lactate accumulation during repeated high-intensity efforts. Thus, the increase in VO_2 max (observed among the football players of the experimental group) is a direct sign of activation and strengthening of the TCA cycle. The VO_2 max index is the main predictor of aerobic endurance and its growth is a key criterion for the effectiveness of physical training programs. In the control group, the growing was only 0.10% ($p>0.05$), indicating the absence of significant changes of the aerobic profile. The dynamics of physiological indicators of the experimental group indicates systemic training adaptation caused by adequate stimulation of aerobic energy supply mechanisms, central regulation of blood circulation and morphofunctional remodeling of the heart. In general, the growth of PWC_{170} and VO_2 max in tandem is a sign of the development of the so-called economic type of blood circulation, when higher mechanical and metabolic efficiency is ensured per unit of time while reducing energy costs per unit of work.

Thus, the results of Table 3 do not only demonstrate the benefits of PHDA, but also emphasize its physiological appropriateness and effectiveness in developing of cardiovascular endurance of adolescent football players. The results presented in Table 3 indicate reliable positive dynamics of key parameters of external respiration of football players in the experimental group. This reflects adaptive shifts on the part of the

bronchopulmonary apparatus, which play a crucial role in ensuring oxygen homeostasis during prolonged physical exertion, in particular, during match conditions.

Each of the indicators presented in Table 2 reflects various aspects of the functional state of the cardiovascular system, and their positive dynamics confirms the formation of highly differentiated hemodynamic regulation of young athletes. SV is the amount of blood ejected by the left ventricle in one contraction. It is one of the most sensitive indicators of central hemodynamic adaptation to physical exertion. A significant increase of SV reflects the growth of the contractile function of the myocardium, the improvement of diastolic filling of the ventricle (mainly due to the increase of the diastolic phase and the increase of venous return) and the increase of the efficiency of myocardial output with each contraction cycle. The SV improvement of teenage football players, is a sign of the formation of an economical type of cardiac activity, when the heart is able to eject a larger volume of blood at a relatively low contraction rate, thereby reducing the cardioenergetic load. During the phase of prolonged defense or in a positional attack, when it is necessary to maintain concentration and simultaneously perform jerky movements (for example, 3-4 accelerations in a row), the increased SV allows the muscular system to be supplied with oxygen without an excessive growing in heart rate. This is especially important in conditions of a lack of time for recovery between game moments.

MBV is an integral indicator of cardiac output per unit of time (the volume of blood circulating through the heart per minute). An increase of MBV indicates a significant growth of the overall transport capacity of the cardiovascular system, and therefore, the body's ability to supply oxygen to actively functioning tissues. Among adolescents, this is especially important, since under conditions of intensive growth, the body requires not only a quantitative but also a qualitative increase of hemodynamic efficiency. The increase of MBV of football players means that their circulatory system is able to respond quickly to the sharply increased metabolic demands typical in match situations. In the second half, especially after the 60th minute, hemodynamic endurance becomes a determining factor in maintaining the game tempo. A player with a high MBV is able to maintain the frequency of sprints, participate in episodes on both halves of the field and recover quickly from high-intensity actions.

CI – minute blood circulation volume, normalized to the athlete's body surface area. This is a particularly important parameter of adolescence, since it compensates for the influence of body weight and height, allowing to compare objectively the functional capabilities of the heart of different athletes. The increase of CI reflects the fact that the heart adapts not only to the volume of the load, but also to individual body sizes, which is especially important in the conditions of a multi-tempo and contact sport, such as football. It also indicates that the heart has become capable of pumping more blood per square meter of body surface, which ensures optimal oxygen supply to tissues under conditions of unstable respiratory and motor rhythms. In conditions of individual bump and run or "one-on-one" fight, is important not only the absolute but also the relative power of the circulatory system. A player with a higher CI is able to maintain the pace even in conditions of microtraumatization, in close physical contact or in a sprint with resistance (for example, when dribbling an opponent in a limited space).

The complex increase of SV, MBV and CI confirms that, under the influence of PHDA, adolescent football players developed a functionally stable, economical and hyperkinetically adapted hemodynamic profile that ideally corresponds to the cyclical-intermittent structure of football activity. This means that the athlete's heart has not only become more powerful, it has become more precise, more resilient and more adapted to the pace of the game, where every moment requires a balance between effort and recovery.

The LVP reflects the mechanical power developed by the left ventricle when ejecting blood into the arterial system. This indicator is an integral characteristic of the strength and energy of cardiac contraction, depending on the stroke volume, arterial pressure and blood ejection time. Its significant increase by 40.3% indicates the increase of the systolic strength of the myocardium and the thickness of the LV wall (physiological hypertrophy); the increase of the ejection fraction (the volume of blood) that leaves the ventricle with each contraction; the increase of the efficiency of the transformation of biochemical energy into mechanical energy (a decrease of the internal viscosity of myocardial fibers and the improvement of the trophism of cardiomyocytes). In the context of adolescence, this reflects the accelerated development of functional cardiac reserve, in which the left ventricle not only increases morphologically, but also qualitatively improves its strength characteristics. During active game situations – for example, during serial rhythm changes (sprint → braking → dribbling → acceleration) – the heart must instantly adapt to fluctuations in metabolic demands. High LVP provides an immediate and powerful perfusion response capable of supporting local microcirculation in actively working muscles of the lower extremities, even with unstable body biomechanics (contact fight, maneuvers with a change of support). The second aspect is resistance to overload. With prolonged pressing or overload of the respiratory system, less adapted players experience a sharp drop of LVP, which is manifested by a decrease of performance, deterioration of the accuracy of the pass, and a slowdown of the pace. An athlete with a developed LVP, this does not happen even in the phase of functional hypoxia, which is essential within the decisive 10-15 minutes of the match. TPR is an indicator of the total resistance provided by the vessels of the systemic circulation to the blood flow. It depends on the tone of the arterioles, the viscosity of the blood and the diameter of the vessels. A decrease of TPR reflects the development of functional vasodilation (a decrease of vascular resistance due to an

increase in the concentration of metabolites (ATP, lactate, H^+) released in the muscles in response to physical work). A slight decrease of TPR (–1.21%) with a significant increase of MBV and PLS indicates a harmonious adaptation of the vascular system – its ability to adjust to the increasing cardiac output without a significant increase in vascular tone. This can be interpreted as a sign of increased vascular compliance, especially peripheral arterioles. During intense physical activity (for example, actively tackling the ball on the opponent's half of the field), the TPR of a trained football player decreases due to the expansion of blood vessels – thus improving the delivery of oxygen and the removal of metabolic products. Adolescents with adequately reduced TPR, blood circulation becomes more economical and targeted, reducing the load on the myocardium and improving tolerance to work against the background of increasing acidification. The absence of sharp jumps of the TPR under conditions of increased MBV is a manifestation of mature vascular regulation, which is critically important during game situations with alternating phases of hyperventilation and breath holding (for example, during sharp braking after a sprint or during a “one-touch” sprint).

The increase of SV, IOC, CI and especially LVP with stability of TPR indicates that the adolescent football players, who underwent the experimental intervention, developed an energy-efficient, hyperkinetic type of blood circulation adapted to the repeated, intermittent, intense muscular activity characteristic of a football match. This hemodynamic configuration ensures a rapid return to the initial heart rate level after episodes of a load; optimal work during the “asymptomatic hypoxia” phase (pressing, additional time); higher “sports resistance” to metabolic stress.

Discussion.

The results of the study demonstrate that the proposed interval-functional program with an emphasis on central hemodynamics has a significant positive effect on aerobic productivity, cardiac pumping function and regulation of vascular tone of 13-15 years old football players. These effects are not isolated but fit into the broader context of adaptation mechanisms involved in systematic exposure to interval aerobic and BFR loads.

The analysis of the obtained results, taking into account previous scientific data, confirms the validity of the approaches which were used. In particular, our data are consistent with the results of the study by Helgerud et al. (2001), who showed that interval training of moderate and submaximal intensity causes a more pronounced increase in stroke volume and VO_2 max of football players compared to uniform work. Similarly, in our study, the increase of SV was 18.2% ($p < 0.001$), and the VO_2 max increased by 9.93% ($p < 0.05$), demonstrate the high efficiency of the interval protocol. Furthermore, the results are consistent with the observations by Kacin & Strazar (2011), who confirmed the potential of BFR training in improving vascular reactivity and activating myocardial hypertrophy without overload. Our data on the increase of left ventricular power (LVP) by 40.3% also confirm that the inclusion of occlusion stimuli (BFR) has a powerful morphofunctional effect with minimal risk (Tyshchenko et al., 2025).

It is important to note that the dynamics of the cardiac index (CI), normalized to body surface area, also has changed statistically reasonably ($p < 0.001$), indicating that the adaptation mechanisms were not limited only to the growth of absolute values, but also affected relative indicators reflecting the functional maturity of the cardiovascular system of adolescents. This is especially important if we mention the observations by Francavilla et al, 2018; Corsaro et al, 2025, who emphasize the need to assess precisely indexed indicators of growing athletes. Unlike the cited works, our study is original in its use of a multicomponent model combining interval work with heart rate control; functional circuit training with BFR; breathing and neurovegetative techniques (neuro-yoga, breath holding, HRV regulation); hypoxic stimuli within the recovery phases.

Our training intervention model is based on multicomponent physiological logic, which combines interval and hypoxic loads, respiratory neuroregulation and partial occlusion methods. Similar approaches have been proposed and tested in other kinds of sport, where the effectiveness of stimulating of aerobic energy reactions through the regulation of vascular tone and endothelial function has been proven (Lisenchuk et al., 2019b; Tyshchenko et al., 2022; Durlević et al., 2025). The positive changes in autonomic regulation that we have presented, expressed in a decrease of heart rate at rest and the increase of HRV, correspond to the modern concepts of psychophysiological balance in team sports (Tyshchenko et al., 2020; Yüce et al., 2025; Al-Wajedi et al., 2025; Vaalayi et al., 2025), and emphasize the importance of including respiratory and neurocirculatory practices into the training process of athletes. This synergistic approach allows us to talk about the formation of an energy-efficient hyperkinetic type of blood circulation, which has been rarely studied in the literature in the context of teenage football. In this aspect, the work expands the existing knowledge in the field of cardiohemodynamic adaptation, since most previous studies were limited to running protocols or loads on a bicycle ergometer. McMillan, K. et al., 2005 used interval running of football players, with an emphasis on endurance. Kvasnytsya et al., 2024; Tyshchenko et al., 2024 made a review of high-intensity interval training in team sports. The analysis of the cardiorespiratory effects of adolescents during cyclic loads was conducted by Granier, C. et al., 2018; Romero-Moraleda et al., 2025, and the review of the physiological effects of HIIT in team sports [Fernández-Jávega et al., 2025; Hussein et al., 2025; Milošević et al., 2025], but without BFR or respiratory regulation, was made by Weston, M. et al., 2014. Our model covers systemic hemodynamic

remodeling and activation of central and peripheral reserves, similar to those implemented successfully into martial arts and team sports (Korobeynikov et al., 2019a; Oliynyk et al., 2021; Tyshchenko et al., 2023).

On the other hand, our results contradict the findings by Faude et al., 2010, who emphasized the insignificant effect of interval training on adolescents with a standard school load. This discrepancy can be explained by the use of additional regulatory and hypoxic stimuli in our protocol, as well as the complex method of periodization of the training cycle. The limitations include a limited sample (one age category, one training center), as well as the lack of instrumental diagnostics (e.g., echocardiography, spiroergometry). However, despite this, the methods used (rheography, PWC₁₇₀, calculation of VO₂ max) are validated and sensitive enough to detect adaptive shifts. In the future, it is worthwhile to make a comparison among athletes of different game roles, as well as to evaluate metabolic stability under competitive conditions.

Future studies should be focused on expanding the age range, inter-seasonal assessment of the stability of adaptations, and the inclusion of comprehensive diagnostics (ultrasound echocardiography, biochemical markers, monitoring of heart rate variability). A promising approach is to combine interval hemodynamic protocols with cognitive-motor tasks, as it has already been tested in our studies for women's boxing teams (Tyshchenko et al., 2023). Therefore, the presented program can be recommended as an effective and physiologically feasible tool for increasing aerobic endurance and functional adaptation of young football players.

Conclusions.

The developed hemodynamic aerobic adaptation program (PHDA), based on interval-functional training with elements of BFR and respiratory regulation, demonstrates high efficiency of the formation of aerobic endurance and functional stability of the cardiovascular system of the adolescent football players. Under the influence of PHDA, a reliable increase of key parameters of central hemodynamics was noted: stroke volume (↑18.2%), minute volume of blood circulation and cardiac index. This indicates the formation of a hyperkinetic, economically advantageous type of blood circulation adapted to the cyclical-intermittent structure of competitive activity in football.

A significant increase of left ventricular power (↑40.3%) indicates the development of physiological myocardial hypertrophy without overload, which reflects the morphofunctional maturity of the heart muscle in response to training stimuli. The increase of the relative PWC₁₇₀ and VO₂ max by 9.93% confirms the activation of aerobic energy supply mechanisms, mitochondrial biogenesis and capillarization of the working muscles, which improves oxygen utilization during repeated loads. A sustained decrease of resting heart rate and the increase of heart rate variability (HRV) demonstrates the activation of parasympathetic regulation and the increase of the effectiveness of recovery processes, which are especially relevant in conditions of a variable game pace. A slight decrease of total peripheral resistance (TPR) with a simultaneous increase in IOC and LVP indicates adaptive vasodilation and increased vascular compliance, which reduces cardiac costs and increases resistance to metabolic stress. In contrast to the control group, the participants of the PHDA showed systemic cardio-hemodynamic adaptation, covering both central and peripheral components of regulation, which makes the proposed model promising for implementation in the practice of training young football players.

The obtained data confirm the need for targeted hemodynamic modeling when constructing training programs of teenage football, taking into account the age characteristics and physiological reserves of athletes.

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Conflict of interest.

The authors state no conflict of interest

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