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Exploring the Link Between Cardiovascular Fitness, Metabolic Syndrome, and Heart Rate Variability in Anesthesiology Residents at Airlangga University

Dhikrulloh Anwar[1], Olga Putri Atsira[2], Prananda Surya Airlangga[3*], Raden Argarini[4]

[1]Department of Anesthesiology and Intensive Therapy, Faculty of Medicine, Universitas Airlangga / Dr. Soetomo General Academic Hospital, Surabaya, Indonesia.

Email ID: dhikrulloh.anwar@gmail.com

[2]Faculty of Medicine, Universitas Airlangga / Dr. Soetomo General Academic Hospital, Surabaya, Indonesia.

Email ID: olgaputriatsira@gmail.com

[3]Department of Anesthesiology and Intensive Therapy, Faculty of Medicine, Universitas Airlangga / Dr. Soetomo General Academic Hospital, Surabaya, Indonesia.

Email ID: prananda-s-a@fk.unair.ac.id

[4]Department of Medical Physiology and Biochemistry, Faculty of Medicine – UNIVERSITAS AIRLANGGA, Surabaya, Indonesia.

Email ID: raden-a@fk.unair.ac.id

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ABSTRACT

Background: Cardiorespiratory fitness (CRF) is a key indicator of aerobic capacity and plays a crucial role in cardiovascular and autonomic nervous system health. Metabolic syndrome (MetS), characterized by abdominal obesity, hyperglycemia, dyslipidemia, and hypertension, increases cardiovascular disease risk and impairs autonomic function. Heart rate variability (HRV) is a noninvasive measure of autonomic balance and cardiovascular health.

Objective: This review explores the interrelationship between CRF, MetS, and HRV, emphasizing its implications for anesthesiology and intensive care residents, who experience high stress and workload.

Methods: A literature review was conducted to assess how CRF influences HRV and mitigates MetS-related autonomic dysfunction.

Findings: Higher CRF is associated with increased HRV, indicating better autonomic regulation, while MetS is linked to reduced HRV and impaired cardiovascular function. Maintaining optimal CRF appears to counteract MetS-related autonomic imbalances, reducing cardiovascular risks in high-stress professions.

Conclusion: Enhancing CRF through structured physical activity may serve as a preventive strategy against MetS-related autonomic dysfunction and cardiovascular disease, particularly for medical professionals exposed to chronic stress. Workplace interventions promoting physical fitness could play a crucial role in safeguarding the well-being of anesthesiology residents.

Keywords: *Cardiorespiratory fitness, Metabolic syndrome, Heart rate variability, Autonomic nervous system, Resident doctors.*

1. INTRODUCTION

Anesthesiology residents face high physical and psychological stress due to long shifts, sleep deprivation, and demanding workloads. These factors, combined with sedentary lifestyles, increase their risk of metabolic syndrome (MetS), a condition characterized by abdominal obesity, hyperglycemia, dyslipidemia, and hypertension.1 MetS is strongly associated with cardiovascular disease (CVD) and autonomic dysfunction, further elevating cardiovascular risk.1

In Indonesia, 21.66% of the population has MetS, with low high-density lipoprotein (HDL) cholesterol (66.41%) as the most prevalent component, followed by hypertension, central obesity, and insulin resistance.2 Regular physical activity and improved cardiorespiratory fitness (CRF) are essential for reducing MetS risk and preventing cardiovascular complications.3 CRF is a key indicator of aerobic capacity, reflecting the efficiency of the circulatory and respiratory systems in delivering oxygen during physical activity. Low CRF levels have been associated with an increased risk of cardiovascular disease and higher mortality rates.4

CRF is typically assessed through maximal exercise testing by measuring maximal oxygen consumption (VO_2max). However, this method requires high costs and trained personnel, making submaximal tests, such as the YMCA step test, a more practical alternative.5 In addition to CRF, heart rate variability (HRV) is another important parameter that reflects autonomic nervous system balance. Reduced HRV is associated with a higher risk of cardiovascular disease and psychological stress, particularly in individuals with demanding workloads, such as emergency or intensive care physicians.6

Given CRF's role in cardiovascular and autonomic regulation, this review examines the relationship between CRF, MetS, and HRV in anesthesiology and intensive care residents. Understanding these links can inform strategies to prevent cardiovascular risks and enhance well-being in high-stress medical settings.

2. LITERARURE REVIEW

Definition of Cardiorespiratory Fitness

Cardiorespiratory fitness (CRF), also known as aerobic capacity, is a key component of physical fitness that reflects the body's ability to sustain dynamic physical activity using large muscle groups for extended periods.7 It is closely linked with the efficiency of the respiratory and circulatory systems in delivering oxygen to skeletal muscles, which is essential for energy production.

Low CRF is a strong independent predictor of CVD and increased mortality risk. In adolescents, CRF is linked to cardiometabolic health, CVD risk, academic performance, and mental well-being, highlighting its importance across different life stages. Given its predictive value, the American Heart Association recognizes CRF as a "vital sign," comparable to major risk factors such as smoking, hypertension, and diabetes.3

As an objective measure of health, CRF can be assessed over time and compared across populations. Its role in predicting mortality and cardiovascular outcomes underscores the importance of improving and monitoring CRF for disease prevention and overall well-being.3

Physiological Basis of Cardiorespiratory Fitness

CRF is influenced by structural and functional adaptations that enhance oxygen transport efficiency. Regular physical activity increases blood volume, myocardial contractility, ventricular compliance, and capillary density, leading to improved cardiac output.3 These adaptations optimize oxygen delivery to working muscles, supporting sustained aerobic activity.

Rowland et al. observed that trained adolescent cyclists exhibited significantly higher cardiac index (cardiac output relative to body surface area) than their untrained peers, despite minimal differences in maximal oxygen extraction.3 This suggests that CRF improvements primarily stem from enhanced cardiovascular efficiency rather than changes in oxygen utilization at the muscle level.

Although often used interchangeably, physical activity and CRF are distinct concepts. Physical activity represents "what they will do", voluntary movement that expends energy, while CRF reflects "what they can do", the physiological capacity to perform sustained activity. Individuals with higher CRF can engage in physical activity more efficiently, creating a self-sustaining cycle of improved fitness and active living.3

CRF is a crucial determinant of overall health. Studies suggest that low CRF is a stronger predictor of mortality than dyslipidemia, hypertension, or obesity. Conversely, high CRF is linked to lower CVD risk and improved long-term health outcomes, reinforcing the need for continuous CRF monitoring and improvement.8

Measurement Tools for Cardiorespiratory Fitness

CRF can be assessed or estimated using various tests and protocols (Table 1). Tests that require maximal effort to measure CRF are known as maximal exercise tests. These tests are typically conducted in medical facilities and are designed to evaluate cardiometabolic parameters, such as respiratory gas analysis, blood pressure, heart rate, and electrical heart activity. In contrast, submaximal exercise tests do not require maximal effort and are often used to estimate CRF based on validated equations or nomograms derived from direct measurements during maximal exercise testing. Submaximal tests provide a viable alternative when maximal testing is not feasible due to safety concerns, environmental constraints, or cost limitations.3

Although submaximal tests are easier to administer, they have a higher margin of error, which may lead to less accurate CRF estimations. However, these methods remain useful for identifying and evaluating individuals with low or suboptimal CRF levels.3

Table 1. Comparison of Selected Tests for Measuring CRF

Test	Description	Ability to Assess CRF	Limitations	Clinical Practice Recommendations
CPET (Cardiopulmonary Exercise Testing - Gas Analysis)	Participants perform progressively challenging exercise while respiratory gases are measured.	+++	Requires specialized equipment.	Gold standard for CRF measurement.
20m Shuttle Run Test (20mSRT - Non-Gas Based)	Participants run or walk between two points on the floor in sync with an audio signal, with increasing frequency.	++	Requires a 20-meter open space.	Modified protocols are available for office-based populations.
Field Running Tests (e.g., 1.5-mile/2400m run)	Participants run a set distance as fast as possible.	++	Results depend on motivation and body composition.	Commonly used in schools.
Step Test (Office-Based or Field-Based)	Participants step up and down on a block of specified height, with each stage linked to an increased step rate.	++	Validity is not well-established.	Portable; can be performed in small spaces.
Walking Tests (e.g., 6-Minute Walk Test - 6MWT)	Participants walk as far as possible within six minutes.	+	Less valid for healthy populations.	Useful for individuals with limited exercise capacity.

Factors Influencing Cardiorespiratory Fitness

Several factors influence CRF, including physical activity, sedentary behaviour, nutrition, genetics, and socioeconomic conditions.

Physical Activity and Sedentary Behavior

While regular physical activity enhances CRF, prolonged inactivity reduces it. By age 15, adolescents spend 75% of their waking hours in sedentary activities, with average sedentary time increasing from 7 hours per day in 2003 to 8.2 hours in 2016 in the UK and US. Prolonged sitting is linked to higher cardiovascular risk, even in physically active individuals. Although moderate-to-vigorous physical activity (MVPA) can mitigate some effects, excessive sedentary time remains detrimental. 3

Nutritional Status and Diet

CRF is affected by body composition and dietary intake. A study on adolescent females found that greater weight loss was linked to improved CRF, likely due to increased lean muscle mass.3 Higher intake of fruits and vegetables is associated with better CRF, as micronutrients support mitochondrial function and muscular efficiency.3

Genetic and Biological Factors

Although CRF has a hereditary component, genetic influences on aerobic capacity are not fully understood. Sex differences also play a role, with males generally experiencing greater CRF improvements due to differences in muscle fiber composition and oxygen utilization. Additionally, preterm birth has been associated with 13% lower CRF, possibly due to reduced lung capacity.3

Socioeconomic and Environmental Influences

Economic disparities contribute to lower CRF by limiting access to structured physical activity, sports facilities, and healthy diets. Studies indicate that greater income inequality is linked to larger declines in CRF, suggesting that environmental and social factors significantly impact fitness levels.3

Given these influences, improving CRF requires a comprehensive approach, including physical activity promotion, sedentary behavior reduction, nutritional interventions, and equitable access to fitness resources.3

Metabolic Syndrome

Mets, also known as insulin resistance syndrome or Syndrome X, is a cluster of metabolic abnormalities that increase the risk of atherosclerotic cardiovascular disease (CVD) and type 2 diabetes mellitus (T2DM).9

Clinically, MetS is defined by the presence of several key markers, including abdominal obesity, hyperglycemia, dyslipidemia, and hypertension.10 According to the National Cholesterol Education Program Adult Treatment Panel III (NCEP-ATP III), MetS is diagnosed when at least three of the criteria in Table 2 are met.11

Table 2. Metabolic Syndrome Treshold

Criterion	Threshold
Abdominal Obesity	>102 cm (men), >88 cm (women)
Triglycerides	≥150 mg/dL or lipid-lowering medication
HDL Cholesterol	<40 mg/dL (men), <50 mg/dL (women)
Blood Pressure	≥130/85 mmHg or antihypertensive use
Fasting Plasma Glucose	≥110 mg/dL or antidiabetic medication

MetS develops due to excessive visceral fat accumulation due to high energy intake and low physical activity contributes to the release of free fatty acids, triggering lipotoxicity and insulin resistance. This leads to hyperinsulinemia and hyperglycemia, further exacerbating metabolic disturbances. Beyond its role in glucose homeostasis, insulin regulates amino acid uptake, protein synthesis, lipoprotein lipase activation, and low-density lipoprotein (LDL) secretion inhibition. An excess of fatty acids and diacylglycerol in skeletal muscle disrupts insulin signaling pathways, reducing glucose transport and utilization efficiency. The cumulative impact of these disruptions contributes to the development of MetS and increases the risk of metabolic and cardiovascular complications.12

This condition not only increases the risk of CVD and T2DM but is also associated with autonomic nervous system (ANS) dysfunction, which is considered one of its complications. ANS dysfunction in the heart is thought to mediate adverse cardiovascular events. Studies indicate that more than 50% of uremic patients undergoing regular hemodialysis experience autonomic neuropathy, linked to baroreceptor dysfunction, reduced alpha-adrenergic receptor regulation, and inappropriate Bezold-Jarisch reflex activation. 13

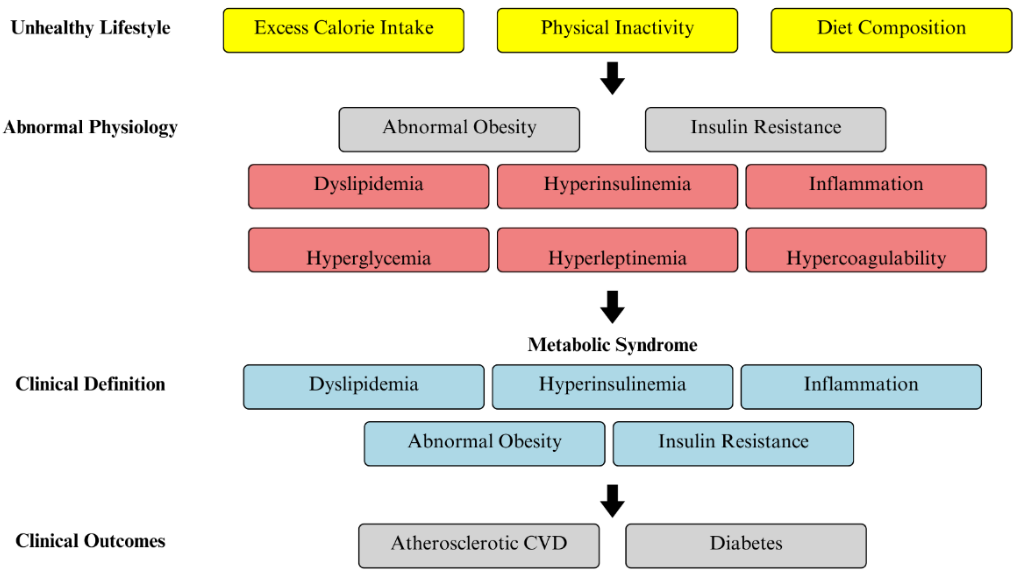

Figure 1. Pathophysiology of Metabolic Syndrome

Unhealthy lifestyle choices contribute to the development of factors that drive metabolic syndrome (grey boxes) and lead to physiological abnormalities. Clinically, disrupted metabolism is measured by the components of metabolic syndrome. This condition subsequently increases the risk of developing atherosclerotic cardiovascular disease (CVD) and diabetes.12

Heart Rate Variability (HRV)

Heart rate variability (HRV) refers to the variation in time intervals between consecutive heartbeats and is used as a noninvasive method to evaluate autonomic nervous system (ANS) function. During mild sympathetic stimulation, HRV may increase. However, under intense or prolonged sympathetic activation, HRV tends to decrease without directly correlating with a reduction in sympathetic activity. Significant reductions in HRV have been linked to an increased risk of sudden cardiac death, all-cause mortality, coronary artery disease progression, and type 2 diabetes mellitus.13

HRV analysis is a valuable noninvasive tool for assessing changes due to aging, disease progression, and other physiological or pathological conditions. HRV modifications are influenced by oscillatory systems and interactions between sympathetic and parasympathetic modulation of heart rate, as well as intrinsic cardiac factors, including extracellular matrix composition, sarcolemma structure (ion channel density and kinetics, gap junction density, lipid composition), myocyte size, adipocyte presence, and fibroblast distribution. The etiology of these changes is often linked to metabolic disorders.10

3. RESULTS

HRV Measurement Domains

Heart rate variability (HRV) can be analyzed using two primary methods: frequency-domain analysis and time-domain analysis (Table 2).13

In frequency-domain analysis, different frequency components of HRV provide insights into autonomic nervous system activity. Very Low Frequency (VLF) is believed to be influenced by vasomotor tone regulation and thermoregulation, while Low Frequency (LF) represents a combination of sympathetic and parasympathetic activity. High Frequency (HF), on the other hand, is closely associated with parasympathetic nerve activity, particularly vagal modulation of heart rate. The LF/HF ratio serves as an indicator of sympathovagal balance, reflecting autonomic nervous system status and sympathetic activity. Another important parameter, Total Power (TP), is the sum of all frequency components, while R–R interval variability (Var) represents the cumulative contribution of all cyclic components affecting HRV during the recording period.11

In time-domain analysis, HRV is assessed based on variations in heart rate intervals over a specific monitoring period, which can range from less than a minute to more than 24 hours. Some of the key metrics in this domain include the Standard Deviation of Normal-to-Normal Intervals (SDNN) and the Root Mean Square of Successive Differences (RMSSD). SDNN, measured in milliseconds, reflects overall HRV and is influenced by both sympathetic (SNS) and parasympathetic (PNS) activity. It is correlated with Ultra Low Frequency (ULF), VLF, LF, and TP power bands and varies depending on measurement conditions. In short-term recordings, HRV is primarily driven by Respiratory Sinus Arrhythmia (RSA), which is mediated by the parasympathetic nervous system, particularly during guided breathing protocols. However, in 24-hour recordings, LF contributions to SDNN become more dominant.13

SDNN is considered the gold standard for cardiovascular risk stratification when recorded over a 24-hour period, as it can predict morbidity and mortality. Based on 24-hour monitoring, an SDNN value below 50 milliseconds is categorized as unhealthy, a range of 50–100 milliseconds indicates a compromised health status, and a value above 100 milliseconds is considered a marker of good health.13

RMSSD, another key metric, is calculated by assessing the successive differences between normal heartbeats in milliseconds, squaring each value, averaging them, and then taking the square root. Although conventional RMSSD recordings are typically five minutes long, ultra-short measurement periods of 10, 30, or 60 seconds have been proposed. RMSSD is particularly useful in assessing short-term HRV and is primarily mediated by vagal (parasympathetic) activity. It has a strong correlation with pNN50 and HF power in 24-hour recordings. Compared to SDNN, RMSSD is more influenced by parasympathetic activity, making it a crucial parameter for evaluating vagal tone.13

Low RMSSD values have been linked to higher risk scores for sudden unexplained death in epilepsy patients. Other indices, such as NN50, pNN50, and RMSSD, are derived from differences in consecutive normal-to-normal (NN) intervals, primarily representing high-frequency oscillations. Since their calculations depend on NN interval differences, these indices are largely unaffected by long-term trends in HRV recordings.14

Beyond HRV, quantifying energy expenditure during physical activity is also essential in understanding metabolic energy disorders. One of the widely used tools for this purpose is Actiheart, a device that combines a heart rate monitor and an accelerometer sensor.15 Designed to assess physical activity levels in populations, Actiheart estimates energy expenditure beyond resting metabolic rates by integrating heart rate data with uniaxial accelerometry measurements.16

Table 3. Heart Rate Variability (HRV) Indices in Time and Frequency Domains

No.	HRV Index	Description	Physiological Significance
1	SDNN (Standard Deviation of NN Intervals)	Measures overall HRV by calculating the standard deviation of all NN intervals	Reflects global autonomic function, including both sympathetic and parasympathetic modulation. Considered the gold standard for cardiovascular risk stratification when recorded over 24 hours, predicting morbidity and mortality.
2	RMSSD (Root Mean Square of Successive Differences)	Square root of the mean squared differences between successive NN intervals	Reflects parasympathetic (vagal/PNS) activity. RMSSD correlates with high-frequency (HF) power but is less influenced by respiratory sinus arrhythmia (RSA).
3	SDANN (Standard Deviation of the Average NN Intervals)	Standard deviation of the mean NN interval for each 5-minute segment, measured over 24 hours	Its role in autonomic nervous system assessment remains debated. Not a direct substitute for SDNN, but closely related. Strongly correlated with minimum heart rate.
4	TI (Triangular Index)	Geometric measurement over 24 hours, calculated from the integral density of the RR interval histogram divided by its height	Distinguishes normal heart rhythms from arrhythmias. A normal rhythm is indicated by TI $\leq$ 20.42 and RMSSD $\leq$ 0.068, while TI > 20.42 suggests arrhythmia.
5	pNN50 (Percentage of NN50 Intervals)	Proportion of successive NN intervals that differ by more than 50 ms	Indicates short-term variations in HRV and serves as a marker of rapid parasympathetic nervous system activity.
6	VLF (Very Low Frequency, 0.0033–0.04 Hz)	Power in the very low frequency range	Associated with long-term regulatory mechanisms, including thermoregulation and hormonal control.
7	LF (Low Frequency, 0.04–0.15 Hz)	Power in the low-frequency range	Represents a combination of sympathetic and parasympathetic influence on HRV.
8	LFn (Normalized Low Frequency Power, 0.04–0.15 Hz)	LF power normalized relative to HF and LF power	Often used as an indicator of sympathovagal balance, where higher values indicate sympathetic dominance (with the constraint that HFn + LFn = 1).
9	HF (High Frequency, 0.15–0.4 Hz)	Power in the high-frequency range	Reflects respiratory sinus arrhythmia (RSA), which is mediated by vagal tone fluctuations. Lower HF power is associated with vagal withdrawal.
10	HFn (Normalized High Frequency Power, 0.15–0.4 Hz)	HF power normalized relative to HF and LF power	Used as a marker of sympathovagal balance, where higher values indicate vagal dominance (with the constraint that HFn + LFn = 1).
11	LF/HF Ratio	Ratio of LF to HF power in frequency-domain HRV analysis	Conceptually represents global sympathovagal balance, but its interpretation remains controversial.

Relationship Between Fitness Levels and Heart Rate Variability

Regular physical exercise plays a crucial role in enhancing cardiovascular fitness and promoting autonomic nervous system adaptation. Declining cardiorespiratory fitness (CRF) is linked to higher morbidity and mortality risks, even in the absence of other risk factors. Individuals with moderate to high cardiovascular fitness—achieved through regular aerobic exercise—have a lower mortality risk from chronic degenerative diseases, particularly cardiovascular and metabolic disorders.17

However, some studies indicate that improving cardiovascular fitness does not always significantly affect HRV in young and middle-aged healthy individuals. This is because autonomic cardiovascular control is already functioning optimally in these individuals. In such cases, exercise does not add further autonomic benefits beyond known cardiovascular effects, such as reduced resting heart rate and faster post-exercise heart rate recovery.17

Nonetheless, HRV analysis remains useful for stress monitoring and cardiovascular conditioning, aiding in exercise planning. Studies suggest that orthostatic testing during training monitoring can improve characterization of acute and chronic exercise adaptation. For example, HRV monitoring in a standing position is necessary to detect long-term HRV reductions after interval training. Schmitt et al. (2015) characterized different fatigue types by analyzing HRV in both supine and standing positions. Thus, while vagal modulation in a supine position may be sufficient for monitoring aerobic training adaptation, full-session HRV monitoring with orthostatic testing is recommended for detecting more complex training adaptations.18

Impact of Metabolic Syndrome on Fitness Levels

VO_2max is considered the gold standard for assessing cardiorespiratory fitness (CRF) and is strongly correlated with various health indicators. Higher daily step counts also correlate with better CRF levels. Regular exercise and improved CRF can positively impact underlying factors of metabolic syndrome (MetS).2,19 Conversely, low CRF increases the likelihood of MetS diagnosis and its associated lipid abnormalities, including low high-density lipoprotein (HDL) and elevated triglyceride levels.4 Low CRF is also a major risk factor for MetS and a predictor of overall mortality. Studies show that individuals with higher CRF have a significantly lower incidence of MetS, making CRF improvement a key preventive strategy.20

Weight loss and CRF improvement have been shown to reduce MetS risk. Most studies use VO_2max as the standard CRF measurement method, but this requires expensive equipment and trained personnel. In large-scale epidemiological studies, alternative CRF measurements include monitoring heart rate during or after submaximal exercise. Additionally, step tests provide a safe, cost-effective alternative for clinical use, including for patients with heart disease or in settings where VO_2max measurement equipment is unavailable. 5

Aerobic capacity, or cardiorespiratory fitness (CRF), is typically expressed in terms of oxygen consumption per kilogram of body weight per minute (mL O_2/kg/min) or in metabolic equivalents (METs), where one MET is equivalent to 3.5 mL O_2/kg/min. Extensive epidemiological, clinical, and basic science research has demonstrated that regular physical activity, structured exercise training, and higher CRF play a significant role in preventing atherosclerotic cardiovascular disease (CVD) and reducing the incidence of coronary heart disease (CHD). Furthermore, individuals with higher CRF before hospitalization for acute coronary syndrome (ACS) or prior to elective or emergency surgery tend to experience better short-term clinical outcomes, highlighting the critical role of CRF in overall cardiovascular health and recovery.21

Exercise intensity should be carefully dosed, as higher exercise volume or intensity generally correlates with lower cardiovascular risk. However, exceeding a certain threshold may introduce adverse effects, such as arrhythmias (e.g., atrial fibrillation), increased coronary calcification, acute coronary syndrome (ACS), and musculoskeletal complications. This "reverse J-curve" phenomenon suggests that exercise benefits do not continue to increase beyond a certain point but may instead elevate health risks. Therefore, moderate-to-vigorous physical activity (MVPA), performed regularly and in a controlled manner, not only supports cardiovascular health but also enhances overall well-being and quality of life.21

4. CONCLUSION

Cardiorespiratory fitness (CRF) is crucial for maintaining cardiovascular health and autonomic balance, particularly in high-stress professionals like anesthesiology residents. This review highlights that higher CRF improves heart rate variability (HRV), counteracting the negative effects of metabolic syndrome (MetS) and stress-related autonomic dysfunction.

Given these benefits, integrating structured physical activity into medical training programs could serve as a preventive strategy against MetS and cardiovascular risks. Medical institutions should prioritize workplace wellness initiatives to support resident health.

Future research should explore long-term CRF interventions and personalized exercise strategies tailored to the demands of medical professionals. By promoting CRF, healthcare institutions can enhance both physician well-being and patient care outcomes.

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