



International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

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ARTICLE TITLE THE ROLE OF ENVIRONMENTAL FACTORS, LIFESTYLE, AND SUPPLEMENTATION IN REGULATING ENDOGENOUS TESTOSTERONE LEVELS IN MEN

DOI [https://doi.org/10.31435/ijitss.4\(48\).2025.4349](https://doi.org/10.31435/ijitss.4(48).2025.4349)

RECEIVED 18 October 2025

ACCEPTED 21 December 2025

PUBLISHED 23 December 2025

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THE ROLE OF ENVIRONMENTAL FACTORS, LIFESTYLE, AND SUPPLEMENTATION IN REGULATING ENDOGENOUS TESTOSTERONE LEVELS IN MEN

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ABSTRACT

Introduction: Testosterone is a crucial hormone for men's health, regulating metabolic, cardiovascular, and psychological functions. In recent decades, a global trend of declining levels has been observed, carrying serious health implications, including an increased risk of metabolic syndrome and reduced quality of life. Although pharmacological treatment for hypogonadism is available, the importance of non-pharmacological interventions is growing. Modifiable factors such as lifestyle (diet, sleep, stress, physical activity), exposure to environmental pollutants (endocrine disruptors), and supplementation (including vitamin D, zinc, adaptogens) are recognized as key regulators of endogenous testosterone production. A systematic analysis of these elements is fundamental for developing effective preventive strategies.

Objective: The aim of this review is to review and synthesize current scientific knowledge regarding the impact of environmental factors, lifestyle, and supplementation on endogenous testosterone levels in men.

Methods: A review of the available scientific literature from PubMed, Scopus, and Google Scholar databases published within the last 20 years was conducted, using keywords related to testosterone, lifestyle, environmental factors, and supplementation.

Results: The review indicates that lifestyle factors such as obesity, poor sleep quality, and chronic stress are strongly associated with lower testosterone levels, while resistance training shows a positive effect. Environmental exposures to endocrine-disrupting chemicals (e.g., BPA, phthalates) and heavy metals (e.g., lead, cadmium) are also linked to hormonal disruption. Supplementation with vitamin D and zinc appears effective primarily in correcting deficiencies, while evidence for adaptogens like Ashwagandha is promising but requires further investigation. The impact of diet composition (e.g., fat intake) is significant, whereas the link between smoking and testosterone remains paradoxical.

Conclusions: Endogenous testosterone levels are influenced by a complex interplay of modifiable lifestyle and environmental factors. Obesity, sleep deprivation, and stress emerge as major negative regulators. While environmental toxins pose a risk, targeted supplementation can be beneficial, particularly for deficiencies. A holistic approach emphasizing lifestyle modifications should be considered the first-line strategy for optimizing male hormonal health.

KEYWORDS

Testosterone, Endogenous Testosterone, Lifestyle, Environmental Factors, Endocrine Disruptors, Supplementation, Hypogonadism, Men's Health

CITATION

Michał Maćkowski, Sandra Balon, Monika Białowąs, Weronika Białowąs, Adam Śmietana, Kacper Piotr Urban, Karolina Maria Dubiel, Natalia Julia Sojka, Piotr Szwed, Jakub Jan Magnowski. (2025) The Role of Environmental Factors, Lifestyle, and Supplementation in Regulating Endogenous Testosterone Levels in Men. *International Journal of Innovative Technologies in Social Science*. 4(48). doi: 10.31435/ijitss.4(48).2025.4349

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1. Introduction

Testosterone is a fundamental androgen, acting as a key regulator of the physiology of the male body. Its effects extend far beyond the reproductive sphere, encompassing the maintenance of metabolic homeostasis, cardiovascular health, bone mineral density, as well as influencing cognitive functions, mood, and overall vitality [1]. An adequate level of this hormone is therefore synonymous with a man's health and well-being at every stage of life. However, over the past few decades, epidemiological data from various parts of the world have begun to paint a concerning picture. Numerous cohort studies conducted in the United States and European countries consistently indicate an observable population trend of declining average levels of total and free testosterone in men [2]. Importantly, this decline is independent of the natural, physiological decrease in androgen levels associated with aging, suggesting the involvement of additional, external factors [2]. Testosterone deficiency, defined as hypogonadism, is becoming increasingly common and affects a significant percentage of men, especially in middle and older age [3]. The clinical consequences of this condition are serious and multifaceted. Low testosterone levels are strongly correlated with an increased risk of developing metabolic syndrome, abdominal obesity, insulin resistance, and type 2 diabetes [4]. Furthermore, it constitutes an independent risk factor for cardiovascular diseases, worsening lipid profiles, and increased markers of inflammation in the body [5]. These metabolic and cardiovascular effects, combined with the negative impact

on the psychological sphere – including increased risk of depression, decreased motivation, and libido – lead to a significant reduction in quality of life and may contribute to increased overall mortality [5]. The scale of this phenomenon elevates it to the status of a significant public health problem, requiring in-depth investigation of its causes and the development of effective coping strategies. Endogenous testosterone production is a precisely regulated process controlled by a hierarchical neurohormonal structure known as the hypothalamic-pituitary-gonadal (HPG) axis. This process is initiated in the hypothalamus, where neurons synthesize and release gonadotropin-releasing hormone (GnRH) in a pulsatile manner [6]. GnRH travels through the portal system to the anterior pituitary gland, stimulating gonadotropic cells to produce and secrete two key gonadotropins: luteinizing hormone (LH) and follicle-stimulating hormone (FSH). The primary stimulus for the testes to produce testosterone is LH. After entering the bloodstream, LH binds to specific receptors on the surface of Leydig cells located in the interstitial tissue of the testes [7]. Activation of the LH receptor triggers a cascade of intracellular signals, central to which is the synthesis of cyclic adenosine monophosphate (cAMP). This, in turn, activates protein kinase A (PKA), which phosphorylates numerous proteins involved in the steroidogenesis process. The key rate-limiting step in testosterone synthesis is the transport of the precursor, cholesterol, from the outer to the inner mitochondrial membrane, a process dependent on the Steroidogenic Acute Regulatory (StAR) protein [7]. Within the mitochondria, cholesterol is converted to pregnenolone, and subsequently, through a series of enzymatic reactions occurring in the smooth endoplasmic reticulum, it is transformed into testosterone [6, 7]. The entire system operates based on a negative feedback mechanism. Both testosterone and its active metabolite, estradiol (formed through aromatization), inhibit the secretion of GnRH in the hypothalamus and LH in the pituitary, which allows for the maintenance of androgen concentrations within a narrow physiological range [8]. The observed global decline in testosterone levels prompts a search for causes beyond genetics and natural aging processes. A growing body of scientific evidence indicates that the lifestyle of modern societies and increasing exposure to environmental factors play a crucial role in the dysregulation of the HPG axis. These factors are modifiable, meaning their identification and understanding of their mechanisms of action hold immense practical and preventive value. Among the most important lifestyle determinants affecting androgen balance are diet, physical activity, sleep quality and quantity, and stress management. Chronic sleep deprivation, even lasting just a week, can significantly lower daily testosterone levels in young, healthy men [9]. Similarly, chronic psychological stress, leading to elevated cortisol levels, can inhibit HPG axis function at both the hypothalamic and testicular levels [8]. Excess body weight, particularly obesity, is one of the strongest risk factors for hypogonadism, partly due to increased aromatase enzyme activity in adipose tissue, which converts testosterone to estrogens [4]. On the other hand, appropriately chosen physical activity, especially resistance training, can stimulate testosterone production [10]. Equally important is the impact of environmental factors, especially the ubiquitous endocrine-disrupting chemicals (EDCs). Compounds such as bisphenol A (BPA), phthalates, and pesticides, present in everyday products, food packaging, and water, can mimic or block the action of natural hormones, disrupting testosterone synthesis and signaling [11]. Concurrently, there is growing interest in the role of micronutrient supplementation, such as vitamin D, zinc, and magnesium, deficiencies of which are common and may impair androgen production, as suggested by systematic reviews [12]. Adaptogens like Ashwagandha (*Withania somnifera*), credited with the ability to modulate stress response and support hormonal balance, may also play a potential role [13]. The aim of this review is to systematically analyze and synthesize current scientific knowledge regarding the impact of key environmental factors, lifestyle elements, and selected supplementation interventions on endogenous testosterone levels in men. The work aims to discuss the mechanisms underlying these interactions and present their potential health consequences, which may form the basis for formulating practical recommendations for the prevention and non-pharmacological support of men's hormonal health.

2. The Impact of Lifestyle Factors on Endogenous Testosterone Levels

Lifestyle, understood as the collection of daily, conscious choices regarding diet, physical activity, sleep hygiene, and stress management, is one of the strongest modifiable factors influencing the body's hormonal homeostasis. In the context of men's health, these elements play a crucial role in the proper functioning of the hypothalamic-pituitary-gonadal (HPG) axis, and neglecting them can lead to a significant reduction in endogenous testosterone production [4, 10]. This chapter provides a detailed analysis of the impact of individual lifestyle components on androgen balance.

2.1. The Role of Diet and Macronutrient Composition

Diet forms the foundation of metabolic and hormonal health. Both the amount of energy supplied and the proportions of key macronutrients, as well as the quality of food consumed, directly translate into the body's ability to synthesize testosterone. Maintaining adequate energy intake and a healthy body weight is crucial for the optimal functioning of the HPG axis. On one hand, long-term, restrictive weight-loss diets leading to a significant caloric deficit are a strong stress signal for the body. In response, the body activates energy-saving mechanisms, including the suppression of reproductive functions. Studies show that chronic energy deficit leads to reduced pulsatile GnRH secretion, which secondarily results in decreased LH and testosterone levels [14, 15]. On the other hand, excessive caloric intake leading to overweight and obesity is one of the strongest risk factors for hypogonadism in men. Obesity, especially abdominal obesity, is associated with increased activity of the enzyme aromatase in adipose tissue, which converts testosterone to estrogens. Elevated estrogen levels exert negative feedback on the HPG axis, further reducing testosterone production. Additionally, obesity often coexists with insulin resistance and inflammation, which also negatively affect androgen synthesis [4]. Western-type diets, rich in processed foods, simple sugars, and unhealthy fats, promote the development of obesity and metabolic disorders, indirectly contributing to lower testosterone levels [16]. Meta-analyses indicate a strong inverse relationship between BMI and testosterone levels, and obesity (BMI ≥ 30 kg/m²) is associated with significantly lower testosterone concentrations, with reductions potentially reaching up to 50% compared to men with normal body weight [17]. Fats, particularly cholesterol, are essential substrates for the production of all steroid hormones, including testosterone [7]. Diets extremely low in fat (below 20% of total calories) are consistently linked to lower levels of total and free testosterone. A meta-analysis of intervention studies showed that switching from a high-fat to a low-fat diet causes a statistically significant decrease in androgen levels, with monounsaturated (MUFA) and saturated (SFA) fats appearing particularly important [18]. This highlights the importance of avoiding drastic fat restrictions in the diet [18]. The ratio of protein to carbohydrates in the diet can also modulate the hormonal environment. Diets very high in protein with concurrent carbohydrate restriction may lead to decreased testosterone levels and increased cortisol concentrations [19]. Carbohydrates play a role in limiting the body's stress response to physical exertion and regulating insulin sensitivity, which indirectly affects hormonal health [19].

2.2. Physical Activity as a Hormonal Modulator

Physical activity exerts a dual effect on testosterone levels, depending on its type, intensity, and volume. Resistance training is the best-documented type of physical exertion that stimulates the hormonal system to increase androgen production. The acute response to resistance training includes a significant, albeit short-lived, increase in testosterone levels. Long-term adaptation to regular resistance training leads to a sustained elevation of baseline hormone levels and beneficial changes in body composition [20]. Training involving large muscle groups, high volume, and moderate to high intensity typically elicits the greatest hormonal response [20]. The impact of endurance training is more complex. Moderate activity is beneficial for cardiovascular health and can help maintain a healthy body weight [10]. However, chronic, prolonged, and exhaustive endurance exercise (e.g., in marathon runners) without adequate recovery and caloric intake can lead to overtraining syndrome. Review papers indicate that this state is often associated with HPG axis disturbances, manifesting as decreased testosterone levels and increased cortisol concentrations [21].

2.3. The Importance of Sleep and Circadian Rhythm

Sleep is a crucial regenerative process during which intense hormonal regulation occurs. Testosterone production is closely linked to the circadian rhythm, reaching peak values in the morning hours after a night's sleep [9, 22]. The peak of testosterone secretion typically occurs during the first REM sleep cycles in the early morning. Both the quantity and quality of sleep are important. Sleep deprivation, even to a minor extent, drastically disrupts this cycle. Restricting sleep to five hours per night for just one week caused a 10-15% decrease in daytime testosterone levels in young, healthy men [9]. Chronic sleep deficiency, as well as disorders like sleep apnea or frequent awakenings (sleep fragmentation), lead to dysregulation of the HPG axis and are associated with lower testosterone levels, fatigue, decreased vitality, and worsened mood [22].

2.4. Psychophysiological Stress and its Impact on the HPG Axis

Modern lifestyle is replete with stressors that have a direct, negative impact on androgen balance. Chronic psychological stress activates the hypothalamic-pituitary-adrenal (HPA) axis, leading to increased cortisol production. Cortisol, known as the stress hormone, acts antagonistically towards testosterone [8]. This mechanism is multi-level: glucocorticoids can inhibit GnRH secretion in the hypothalamus, reduce pituitary sensitivity to GnRH (thereby lowering LH secretion), and directly inhibit steroidogenesis in Leydig cells within the testes by affecting the expression of key enzymes [8, 23]. Consequently, men experiencing chronic stress often exhibit clinically lower testosterone levels, which can exacerbate the negative effects of stress, creating a vicious cycle [23].

2.5. Stimulants and their Impact on Androgen Balance

Alcohol consumption, especially in large quantities and chronically, has a proven toxic effect on the testes. Ethanol and its metabolite, acetaldehyde, directly damage Leydig cells, inhibiting enzymes necessary for testosterone synthesis [24]. Alcohol abuse also burdens the liver, disrupting hormone metabolism. The result is decreased testosterone levels and an increased risk of hypogonadism [24]. The relationship between tobacco smoking and testosterone levels is paradoxical. A comprehensive meta-analysis of observational studies showed that current male smokers have statistically higher total testosterone levels compared to men who have never smoked [25]. However, it must be emphatically stressed that this hormonal effect is insignificant in the face of overwhelming evidence of the devastating negative impacts of smoking on cardiovascular and pulmonary health, cancer risk, and reproductive functions [25].

3. Environmental Factors and Male Hormonal Function

Beyond conscious lifestyle choices, men's hormonal health is also determined by ubiquitous, often unnoticed, exposure to environmental factors. The modern environment abounds in thousands of synthetic chemical compounds, many of which have the ability to disrupt the body's delicate endocrine balance [11]. These substances, present in the air, water, soil, and everyday products, can negatively affect the synthesis, metabolism, and action of testosterone, contributing to the observed global trend of its declining levels in the male population.

3.1. Endocrine Disrupting Chemicals (EDCs) in Daily Life

Endocrine Disrupting Chemicals (EDCs) are exogenous chemical compounds or mixtures that interfere with any aspect of hormone action. Their negative impact on the male reproductive system is particularly well-documented [11]. The mechanisms of action of EDCs are diverse and may include mimicking the action of natural hormones (e.g., estrogens), blocking hormone receptors (anti-androgenic effect), and interfering with the synthesis, transport, and metabolism of hormones, including testosterone [11]. Bisphenol A (BPA) is one of the most widely used chemicals in the production of polycarbonate plastics and epoxy resins. BPA exposure is widespread and harmful, although some large population studies have shown ambiguous or even positive correlations between BPA and testosterone [26]. Concurrently, BPA is a well-known compound with estrogenic activity, which, as literature reviews show, can disrupt the balance of the HPG axis and is linked in animal studies to negative impacts on the reproductive system [27]. Phthalates are a group of chemicals used as plasticizers and solvents. Phthalate exposure is associated with reproductive disorders in men, including reduced semen quality and lower testosterone levels. Systematic reviews of epidemiological literature confirm an association between exposure to certain phthalates and changes in male reproductive hormone levels [28]. The anti-androgenic mechanism of phthalates primarily involves interference with testosterone synthesis in Leydig cells [29]. Many compounds used in agriculture exhibit endocrine-disrupting properties. Studies on agricultural workers indicate an increased risk of hormonal disorders, including reduced testosterone levels. Some of these compounds may act as androgen receptor antagonists [30].

3.2. The Impact of Heavy Metals

Heavy metals, such as lead and cadmium, are toxic environmental pollutants. Their accumulation in the body has a proven negative effect on the reproductive system. Chronic lead exposure is associated with HPG axis suppression. It can disrupt LH secretion and directly damage Leydig cells. Population studies show that men with higher blood lead levels have lower testosterone levels [31]. Cadmium accumulates in the testes and exhibits cytotoxic effects on Leydig and Sertoli cells. Observational studies consistently link higher cadmium concentrations with lower testosterone and higher LH levels, possibly indicating primary testicular failure [32].

4. The Role of Supplementation in Supporting Endogenous Testosterone Production

Interest in non-pharmacological methods for optimizing testosterone levels has led to the increased popularity of dietary supplements. The market is abundant with preparations purported to support male hormonal balance. However, a critical, evidence-based approach is crucial to distinguish interventions with proven efficacy from those whose effects are unconfirmed or based on weak premises. The effectiveness of supplementation is most often conditional on the pre-existence of a deficiency of the particular component in the body.

4.1. Key Vitamins and Minerals

Deficiencies of certain micronutrients are common in the general population and can significantly impair the process of testosterone synthesis. Replenishing these deficiencies is a fundamental step towards optimizing hormonal health. Vitamin D is a steroid prohormone, and its receptors (VDR) are found in Leydig cells and the pituitary gland, among other tissues. Observational studies consistently show a positive correlation between serum 25(OH)D concentration and testosterone levels in men [33]. A systematic review of the literature suggests a potentially beneficial role of adequate vitamin D status for male fertility and hormonal health, especially in deficient men, and one key intervention study showed that annual vitamin D supplementation in deficient men led to an approximately 25% increase in total testosterone levels [12, 34]. The mechanism of action may involve stimulating steroidogenesis and inhibiting aromatase [35]. Zinc (Zn) is a trace element crucial for the functioning of the HPG axis [36]. In zinc-deficient men, supplementation leads to an increase in testosterone levels. In men with normal zinc levels, additional supplementation does not provide further benefits [36]. Magnesium (Mg) affects testosterone bioavailability by inhibiting its binding to SHBG, leading to an increase in free testosterone [37]. Supplementation, particularly combined with physical activity, may increase testosterone levels [37].

4.2. Herbal Supplements and Adaptogens – A Review of Evidence

Adaptogens are plant-derived substances that increase resistance to stressors. Ashwagandha (*Withania somnifera*) is one of the best-studied adaptogens. It demonstrates the ability to lower cortisol levels, which may secondarily affect the HPG axis [13]. Randomized trials have shown that ashwagandha supplementation led to a statistically significant increase in testosterone levels (one study reported a 14.7% greater increase than placebo), improved semen parameters, and increased muscle strength and mass in men [13, 38]. Evidence for the effectiveness of *Tribulus terrestris* in raising testosterone is weak [39]. *Trigonella foenum-graecum* (Fenugreek) has shown potential in some studies to increase testosterone levels, but results require confirmation [40].

5. Discussion

This literature review has provided comprehensive evidence that endogenous testosterone levels in men result from complex interactions between genetic factors, the aging process, and a broad spectrum of modifiable lifestyle elements and environmental exposures. Analysis of the collected material allows for the synthesis of key observations, indication of practical implications, and identification of areas requiring further research. The review demonstrated that certain lifestyle factors have an exceptionally strong and well-documented impact on androgen balance. Among the most significant are obesity, sleep quality, and chronic stress. Obesity, through mechanisms of increased aromatization and insulin resistance, is one of the most potent suppressors of the HPG axis in developed countries, leading to significant testosterone reductions potentially reaching up to 50% [4, 17]. Equally potent, though often underestimated, is the impact of sleep deprivation. Studies unequivocally show that even short-term sleep restriction (to 5 hours per night) drastically reduces testosterone levels by 10-15%, which has immediate effects on well-being and vitality [9, 22]. Chronic stress, manifesting as elevated cortisol levels, constitutes another key element inhibiting testosterone synthesis, consistent with findings from key review papers [8, 23]. The influence of diet and physical activity is more nuanced. While extreme caloric restriction and low-fat diets clearly correlate with lower androgen levels [14, 18], the optimal dietary composition is still debated. Similarly, for physical activity – resistance training is a proven stimulant, whereas excessive endurance exercise can lead to hormonal suppression [20, 21]. However, these factors hold enormous preventive and therapeutic potential, demonstrated in intervention studies where comprehensive lifestyle modifications led to significant improvements in hormonal parameters [10]. The impact of environmental factors, such as EDCs (e.g., BPA, phthalates) and heavy metals, is increasingly well-documented, yet the strength of their impact at the individual level is harder to estimate [11, 28, 31]. The

ubiquity of these compounds and the difficulty in avoiding exposure pose a challenge. Although population studies show clear correlations, translating these findings into individual risk requires further research. Regarding supplementation, the evidence is strongest for correcting existing deficiencies, especially of vitamin D and zinc [12, 34, 36]. These interventions, which can lead to significant increases in testosterone levels (e.g., ~25% for vitamin D [34]), can be considered effective and safe in deficient individuals. For herbal supplements like Ashwagandha, there is promising evidence from clinical trials (T increase ~15% greater than placebo [13]), but these are often conducted on small groups and require replication [13, 38]. Many popular preparations, like *Tribulus terrestris*, lack confirmation of their efficacy in robust studies [39]. A key conclusion from the review is that the analyzed factors do not act in isolation but form a network of interconnections. An obese man leading a sedentary lifestyle, experiencing chronic stress, sleeping too little, and consuming a micronutrient-poor diet creates an "ideal" environment for developing hypogonadism. In such a case, supplementing zinc or vitamin D alone, without addressing fundamental lifestyle issues, is likely to yield limited results. This phenomenon of synergy has significant clinical implications. The approach to a patient with low testosterone should be holistic. Instead of hastily implementing pharmacological testosterone replacement therapy (TRT), the first-line intervention should be in-depth education and implementation of lifestyle changes. Weight reduction, optimization of sleep hygiene, implementation of stress management techniques, and introduction of regular resistance training and a balanced diet form the foundation of therapy. Such an approach not only naturally supports endogenous testosterone production but also brings numerous additional health benefits, reducing the risk of cardiovascular and metabolic diseases strongly linked to low testosterone levels [5]. This review, like any narrative review, has limitations. No statistical meta-analysis was performed, and literature selection, despite a structured approach, might be subject to some bias. Many analyzed studies, especially concerning environmental factors, are observational, allowing for correlation but not causation to be established. Further long-term, randomized controlled trials evaluating the effectiveness of comprehensive lifestyle interventions are necessary. Research on the impact of ever-newer environmental chemicals on the male hormonal system must continue. Understanding the mechanisms through which herbal supplements might affect the HPG axis is also a crucial area, needed to separate marketing from sound science.

6. Conclusions

Based on the conducted review of scientific literature, the following conclusions can be drawn, directly addressing the aim of the work:

1. Endogenous testosterone levels in men are dynamically regulated by a broad spectrum of modifiable factors related to lifestyle and the environment. The observed global decline in this hormone's concentration in populations is a multifactorial phenomenon extending beyond natural aging processes.
2. Among lifestyle factors with the strongest, negative, and best-documented impact on testosterone levels are excess body weight (obesity), chronic sleep deprivation, and chronic psychophysiological stress. Conversely, regular resistance training and a diet ensuring adequate caloric and fat intake are key stimulating factors.
3. Increasing exposure to endocrine-disrupting chemicals (EDCs), such as bisphenol A and phthalates, and heavy metals poses a significant, though often underestimated, threat to male hormonal health, acting at multiple levels of the hypothalamic-pituitary-gonadal axis.
4. Micronutrient supplementation, particularly with vitamin D and zinc, is an effective strategy for supporting testosterone production, but its effectiveness is highest when correcting existing deficiencies. Evidence for the efficacy of many popular herbal supplements is limited and requires further verification in rigorous clinical trials.
5. Due to the complexity and interplay of the discussed factors, the approach to preventing and treating low testosterone levels should be holistic, with lifestyle modifications constituting the fundamental first-line intervention.

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Funding statement: The study did not receive special funding.

Conflict of Interest Statement: The authors report no conflicts of interest.

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