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IMPLICATIONS FOR PERFORMANCE, HEALTH, AND TRAINING

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IRON DEFICIENCY WITHOUT ANEMIA IN ATHLETES: IMPLICATIONS FOR PERFORMANCE, HEALTH, AND TRAINING

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ABSTRACT

Objectives: This review synthesizes current evidence regarding the impact of IDNA on athletic performance. It also covers physiological mechanisms, diagnostic strategies, as well as potential nutritional and training implications.

Methods: The literature search was conducted in the PubMed database. The search terms were related to iron deficiency, iron status, non-anemic states, athletes, performance, and endurance. Athletes with low iron stores and normal hemoglobin concentrations were the subject of this study, which included original research and reviews. Studies consisting of iron deficiency anemia (IDA) or non-athletic populations were excluded from the paper. A narrative synthesis was performed.

Key Findings: IDNA is a common condition among athletic populations, which can be associated with reduced aerobic capacity. Affected athletes have a decreased probability of achieving high VO₂-based performance thresholds. Therefore, athletes should be seasonally screened for IDNA using ferritin with CRP. Diagnostic accuracy can be improved by selective use of transferrin saturation and soluble transferrin receptor (sTfR). Iron supplementation efficacy depends on the severity of iron deficiency. Performance benefits are most consistent in individuals with ferritin levels below 20 µg/L.

Conclusions: Endurance performance and training efficiency are especially at risk of being negatively affected by IDNA. The research shows that athletes at a higher risk of IDNA should be advised to conduct regular screening. Moreover, there is a lack of analysis focused on ferritin cut-offs and intervention protocols that would benefit athletic populations.

KEYWORDS

Iron Deficiency, Athletes, Non-Anemic, Ferritin, Aerobic Performance

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1. Introduction

Iron is one of the most important trace elements in the human body. By participating in oxygen transport, oxygen storage, and mitochondrial metabolism, it plays a key role in aerobic respiration (Dutt et al., 2022). Iron deficiency is commonly associated with low hemoglobin concentration; however, these terms are not always synonymous (Al-Naseem et al., 2021).

The functional fraction of iron—incorporated into hemoglobin, myoglobin, and enzymatic proteins—is supported by storage reserves located primarily in the liver, spleen, and bone marrow (Ganz & Nemeth, 2012). Depletion of iron stores may occur long before changes in hemoglobin concentration become apparent (Al-Naseem et al., 2021).

Iron status is assessed using multiple biomarkers, including ferritin and transferrin saturation (TSAT), which reflect iron availability in the body, as well as hemoglobin, which represents a late marker of deficiency. Another important parameter is hepcidin concentration, which regulates iron availability (Vogt et al., 2021).

A significant clinical condition is iron deficiency without anemia (IDNA), in which hemoglobin levels remain within the normal range while total body iron is reduced, most commonly identified by decreased serum ferritin concentration (Al-Naseem et al., 2021). The body is able to compensate for iron deficiency by mobilizing iron from storage pools, which explains why a decline in hemoglobin may occur only at a later stage of the condition.

The complex and dynamic regulation of iron metabolism may result in iron deficiency remaining undetected in standard laboratory diagnostics. The absence of anemia often excludes iron deficiency as a potential cause of nonspecific symptoms such as fatigue or reduced exercise capacity (Al-Naseem et al., 2021). This is particularly relevant in athletic populations, in whom increased metabolic demands for iron mean that even subclinical deficiencies may negatively affect training adaptations and the achievement of performance goals (Clénin et al., 2015).

Athletes differ from the general population due to their high metabolic demands and frequent exposure to exercise-induced physiological stress. Increased oxygen requirements during physical exertion lead to greater utilization of iron in processes such as erythropoiesis, meaning that even minor deficiencies of this element may have functional consequences in this group (Clénin et al., 2015).

Although iron metabolism has become a topic of growing interest in the context of athletic performance, iron deficiency without anemia (IDNA) remains an underrecognized condition in this population. Available reviews most often address iron deficiency in general terms or focus on iron deficiency anemia, whereas data specifically related to IDNA are scattered and often inconsistent. Therefore, the aim of this review is to summarize current evidence regarding IDNA in athletic populations, with particular emphasis on at-risk groups, physiological mechanisms, diagnostic strategies, and nutritional and training interventions that influence iron metabolism and may support optimization of the training process.

2. Methods

2.1. Literature Search Strategy

The literature search was conducted in the PubMed database. It covered publications between 1980 and 2025. Past studies have been reviewed to provide definition of medical terminology. The search terms were related to iron deficiency, iron status, non-anemic states, athletes, aerobic capacity, performance, endurance and related MeSH terms. Additional studies were identified manually by the review of the reference lists of key articles.

2.2. Inclusion and Exclusion Criteria

Athletes or physically active individuals were the subject of this study, which included original research and review articles. The analysed articles reported iron status biomarkers such as ferritin, hemoglobin, transferrin saturation, soluble transferrin receptor or hepcidin and assessed performance, physiological or training-related outcomes.

Studies were excluded if they focused exclusively on iron deficiency anemia, were conducted in non-athletic populations, consisted solely of case reports or lacked biomarker data or relevant performance measures.

2.3. Data Extraction and Synthesis

Data extraction focused on biomarkers (ferritin, hemoglobin, transferrin saturation, soluble transferrin receptor, hepcidin), aerobic performance (VO_2 max, VO_2 peak, endurance events), and non-performance outcomes (fatigue, mood, nutritional intake, supplementation protocols and training load). In order to limit any irregularities in study design and outcomes, the results were synthesised in a narrative review.

3. Epidemiology and Prevalence of IDNA in Athletes

3.1. Prevalence Across Disciplines and Sex

The prevalence of iron deficiency without anemia among athletes is associated with both sex and the type of sport performed. In a large cohort study, it was found that 19.7% of athletes had reduced serum ferritin concentrations according to the criteria adopted by the authors, while a proportion of these individuals did not present with reduced hemoglobin levels. Women were more frequently affected by reduced ferritin levels than men (64.5% vs. 26.8%). At the same time, an association was observed indicating that the risk of iron deficiency in women decreases with increasing age (Keller et al., 2024).

Similar observations have also been reported in recreational sports. In another study focusing on iron metabolism in recreational athletes, 29% of women and 4% of men were reported to have iron deficiency without anemia (Sinclair & Hinton, 2005).

This phenomenon is also observed in young athletes. In a study conducted by Rowland et al., iron status parameters were compared in the same group of long-distance runners before and after an intensive training season. In both sexes, a noticeable increase in the proportion of individuals with iron deficiency was observed, particularly among girls. These findings suggest that iron deficiency without concomitant anemia represents a relevant clinical issue in young athletes, often exacerbated by physical exertion (Rowland et al., 1987).

The type of sport discipline practiced is also not irrelevant to hematological parameters. Athletes engaged in predominantly aerobic exercise (long-distance running) exhibit poorer values of selected hematological indices related to iron metabolism compared with those training under predominantly anaerobic conditions (Osman et al., 2024). Multiple factors contribute to these differences. During intensive training, endurance athletes are more susceptible to iron loss through sweating, exercise-induced hemolysis, and

microbleeding within the gastrointestinal tract. Furthermore, intense physical exertion, by stimulating an inflammatory response,

indirectly leads to an increase in hepcidin, thereby impairing iron absorption and potentially exacerbating iron deficiency (Sims et al., 2022). In summary, based on the available evidence, endurance sport can be considered a probable risk factor for iron deficiency without anemia (IDNA).

3.2. Risk Factors

As indicated by the presented data, female sex - particularly in young, menstruating women - is one of the factors predisposing to the development of iron deficiency without anemia (IDNA). The study by Mayer et al., conducted in a group of physically active women, indicates that menstrual blood loss constitutes an independent risk factor for reduced iron stores, independent of dietary iron intake, and does not necessarily coexist with anemia (Mayer et al., 2020).

Another risk factor is dietary iron intake and bioavailability that are inadequate in relation to the athlete's requirements. This is influenced by the adopted dietary pattern—consumption of less bioavailable forms of iron and a diet low in vitamin C, which supports iron absorption—which, when combined with a high training load, may predispose to the development of iron deficiency. Endurance athletes are particularly exposed to such a profile of iron metabolism (Rodriguez et al., 2009).

Intensive training overload also constitutes a risk factor for the development of iron deficiency without anemia. This mechanism is associated with increased exercise-induced iron losses, including hemolysis, iron loss through sweat, and gastrointestinal microbleeding, as described above.

As indicated by the presented data, iron deficiency without anemia has a multifactorial etiology, and its pathogenesis is influenced by sex, nutrition, and training load.

4. Physiological Mechanisms Linking IDNA and Performance

4.1. Iron in Oxygen Transport and Mitochondrial Function

Iron is an integral part of systemic oxygen transport and intramuscular energy production. In both hemoglobin and myoglobin iron is the central ion for the binding of oxygen. Hemoglobin delivers oxygen to peripheral tissues, as myoglobin is responsible for oxygen storage and diffusion from the capillaries to skeletal muscle cells. During aerobic exercise, oxygen storage in muscle cells supports oxidative ATP production under conditions of increased oxygen demand (Beard, 2001).

At the cellular level iron participates in electron transfer reactions as a part of iron-sulfur enzymes and heme-containing enzymes (cytochromes). In the family of cytochromes heme is an active site, which accepts or donates electrons in reversible redox transitions between ferric (Fe^{3+}) and ferrous (Fe^{2+}) states. These proteins are essential to mitochondrial oxidative phosphorylation and ATP production. In iron deficiency conditions, there is a decline in activity of these complexes, particularly Complex IV (cytochrome c oxidase) and Complex I. As a consequence the ATP production is lowered (Walter et al., 2002).

Animal research indicates that subclinical iron deficiency can compromise mitochondrial oxidative function. Mackler in his rat model demonstrated that dietary iron restriction reduced mitochondrial oxidative phosphorylation rates in skeletal muscles, relative to control conditions (Mackler et al., 1984). Further suggestions are given by Walter, whose finding proves that iron deficiency may also increase oxidative stress, leading to mitochondrial dysfunction (Walter et al., 2002). Collectively, these studies imply that in conditions of iron deficiency, ATP production is lowered, consequently limiting the metabolic efficiency required for endurance performance.

4.2. Effects on Aerobic Capacity

Recent evidence indicates that iron deficiency, even without anemia, is associated with reduced aerobic capacity in athletes. According to a study conducted on a group of 1190 competitive athletes, individuals with low iron stores presented with lower peak oxygen uptake ($\text{VO}_{2\text{peak}}$) and reduced possibility of achieving higher aerobic performance thresholds (Keller et al., 2024). In DellaValle observational study of female rowers from New York State, athletes with iron depletion presented slower endurance performance outcomes than ones with normal iron status (DellaValle & Haas, 2011). It supports a role for iron in sustaining optimal aerobic metabolism.

4.3. Submaximal and Anaerobic Performance

In contrast to the well-documented effects of iron deficiency on aerobic exercise performance, data regarding its impact on anaerobic exercise remain limited. A systematic review by Pengelly et al. reported that evidence for effects of iron deficiency without anemia on performance parameters other than endurance, including strength and power, was limited. When hemoglobin concentrations were within normal ranges, no

consistent reductions in strength or power outcomes were observed across the included studies. However, these findings should be interpreted with caution due to heterogeneity between studies and individual variability (Pengelly et al., 2025). Overall, the available evidence regarding anaerobic exercise performance in athletes with iron deficiency without anemia remains inconclusive and warrants further investigation.

4.4. Non-Performance Health Consequences

Iron deficiency without anemia is not limited exclusively to consequences related to physical exercise. Fatigue is a symptom classically associated with anemia; however, it may also occur in the absence of its laboratory indicators.

In a randomized, placebo-controlled study, a group of women suffering from chronic fatigue of unknown etiology was evaluated. The majority of participants were characterized by reduced serum ferritin concentrations with normal hemoglobin values. The results of the study indicate that one month of iron supplementation significantly reduced fatigue levels compared with the placebo group. The greatest benefits of supplementation were observed in women with ferritin concentrations $<50 \mu\text{g/L}$ (Verdon et al., 2003). It should be noted, however, that this study was conducted in the general population rather than among athletes, which may limit the direct translation of these findings to athletic populations.

In another study, a group of female soldiers was subjected to intensive military training. The aim of the study was to determine whether iron deficiency affects mood and perceived vitality in women under conditions of substantial physical load. It was demonstrated that participants receiving placebo were characterized by lower mood scores compared with women who received iron supplementation during the training period (McClung et al., 2009). These findings may suggest that iron status plays a role in maintaining psychological well-being during periods of high physical strain.

Iron is an essential element required for the proper functioning of the immune system and the nervous system, including cognitive processes. However, at present, there are no data describing the impact of iron deficiency without anemia on immune function or cognitive function in athletic populations. Taking the available data into account, it cannot be excluded that this issue may also be present in this population, particularly among athletes undergoing intensive training.

In summary, the available evidence suggests that iron deficiency without anemia may affect well-being and psychophysical functioning; however, the lack of studies conducted in athletic populations precludes a definitive assessment of the extent and significance of these consequences under training conditions.

5. Screening and Monitoring Strategies

5.1. Biomarkers

Screening for iron deficiency in athletes requires individualised biomarker strategies. Ferritin remains the main indicator of iron stores. In the general population WHO suggested that ferritin level indicating depleted stores is $<15 \text{ ng/mL}$. In athletic cohorts it can lead to underestimating. According to Roy, who analysed data of 629 athletes, the first step should be ferritin analyses. When ferritin level is $<35 \text{ ng/mL}$ further biochemical analyses should be conducted, including transferrin saturation (TSAT) and soluble transferrin receptor (sTfR). Roy claims it improves diagnostic accuracy and differentiation between prelatent and latent deficiency of iron (Roy et al., 2022). Complementary findings are presented by Husarova, who indicate that ferritin levels between 20–50 ng/mL are common in athletes and may represent suboptimal iron status. In her analysis females were disproportionately affected (Husarova et al., 2024). Another scholar, Clénin, also supports the recommendation that a cut-off for ferritin of 30 ng/mL is appropriate among athletes (Clénin et al., 2015). He also suggested that prior to altitude training the ferritin value of 50 ng/mL should be attained, as demands are increased.

Ferritin is an acute-phase protein, therefore during screening C-reactive protein (CRP) levels should be tested to distinguish true iron depletion from inflammation-driven elevations in ferritin (Roy et al., 2022).

Across the studies one can note that timing of blood sampling is essential, as exercise modulates iron biomarkers. For example, in Peeling research, post exercise hepcidin levels vary by ferritin category. Athletes with higher iron stores show a stronger post-exercise increase in hepcidin, whereas athletes with low iron stores have a blunted response (Peeling et al., 2014). Another longitudinal monitoring, conducted by Zügel, during a 4-week high-load training camp showed that hepcidin and ferritin fluctuate with training load. No parallel shifts in hemoglobin were observed (Zügel et al., 2019).

5.2. Practical Screening Protocols

Athletes are recommended to undergo systematic screening, as prevalence of IDNA in this group remains high. In low-risk group testing should be conducted once a year. Whereas in high-risk groups

(endurance athletes, menstruating females and those with a history of deficiency) there should be two or more assessments per season (Roy et al., 2022, Husarova et al., 2024, Clénin et al., 2015).

Blood sampling should be performed in the morning, in a rested state and at least 24–48 hours after intense training. This minimalises exercise-induced fluctuations in ferritin and hepcidin (Peeling et al., 2014, Zügel et al., 2019).

The screening algorithm should begin with hemoglobin, ferritin and CRP. If ferritin is $<30\text{--}35$ ng/mL or symptoms suggest iron-related fatigue, TSAT and sTfR can be added to differentiate depleted stores from functional deficiency (Roy et al., 2022).

6. Nutritional and Training Implications

6.1. Dietary Strategies

Numerous studies indicate that heme iron is characterized by significantly higher bioavailability than non-heme iron. As a result, iron deficiency is more likely to develop in individuals who limit the consumption of animal products, including vegetarians. It has been documented that not only the amount of iron is important, but also its potential for absorption. The absorption of heme iron is relatively less susceptible to changes induced by meal composition. In contrast, non-heme iron absorption is closely related to meal composition and the intestinal environment.

In the study by Hallberg and Hulthén et al., the authors focused on the development of an algorithm to estimate which factors enhance and which inhibit iron absorption from a meal, particularly non-heme iron, using radioisotopic iron tracers (Hallberg & Hulthén, 2000). The promoting effects of vitamin C and the so-called “meat factor” on iron absorption were confirmed, as well as inhibitory effects of phytates, polyphenols present in beverages (such as coffee and tea), and calcium. Under the conditions of the conducted study, coffee and tea reduced iron absorption by more than half.

Vitamin C is the strongest enhancer of iron absorption, acting by reducing iron to its more readily absorbable ferrous form (Fe^{2+}). Its effect is dose-dependent and is most pronounced in meals containing polyphenols; however, it also increases iron absorption in meals devoid of these compounds. Vitamin C exhibits a limited effect on iron absorption in meals containing meat or dairy products.

Calcium also affects iron absorption. Its inhibitory effect applies to both non-heme and heme iron, impairing their absorption in a manner dependent on the amount consumed within a meal. Calcium is a particularly relevant inhibitor in the context of athletes, who often follow high-protein diets that include large amounts of dairy products and additionally supplement calcium.

Taken together, these findings indicate that, in the context of iron deficiency without anemia (IDNA), attention should be paid not only to the amount of iron consumed, but also to meal composition and the presence of factors influencing its final bioavailability.

6.2. Supplementation.

Evidence on iron supplementation in athletes with iron deficiency without anemia (IDNA) indicates that performance responses depend on the severity of iron deficiency. A systematic review reported that studies demonstrating performance improvements typically used a ferritin threshold of ≤ 20 $\mu\text{g/L}$ and employed oral iron supplementation. This suggests that performance benefits are most consistent in individuals with very low iron stores (Rubeor et al., 2018).

Additionally, in a large analysis of 23 studies, including 669 athletes, endurance performance improved by 2% to 20% with the supplementation of 100 mg of elemental iron per day for up to 56 days via the oral route or bi-daily via parenteral administration over 8–10 days (Pengelly et al., 2025). In these findings, one can note that supplementation may be more efficient in athletes with very low ferritin levels, and that positive performance effects are variable across studies.

Oral iron is a preferred route of supplementation due to its safety and accessibility. Limitations include possible gastrointestinal intolerance and variable absorption in individuals (Rubeor et al., 2018). There is still no clear consensus within the group of IDNA athletes on the optimal dose, frequency, or duration of supplementation. Individual protocols should be tailored based on monitoring of iron status during supplementation (Rubeor et al., 2018).

6.3. Training Modifications

As previously indicated, physical exercise has an indirect effect on hepcidin concentration. In the study by Barney et al., hepcidin levels were assessed in women and men trained in long-distance running (Barney et al., 2022). It was demonstrated that intense physical exercise leads to an increase in hepcidin concentration, which reaches peak values approximately 3 hours after exercise cessation, resulting in a significant reduction

in iron absorption. In contrast, the study by McCormick et al. observed that iron was best absorbed from a meal consumed in the early post-exercise period, before the postprandial peak in hepcidin occurred (McCormick et al., 2019). Collectively, these data may indicate the existence of a so-called “window of opportunity,” encompassing the early post-exercise period, during which iron absorption from ingested meals is most efficient.

It is worth noting that in the study by Barney et al., this relationship was more pronounced in men than in women, which may suggest the presence of sex-specific differences in the hepcidin response to physical exercise, potentially relevant for the planning of nutritional and training strategies, although requiring further investigation.

Awareness of these relationships is particularly important in athletes with iron deficiency without anemia (IDNA), in whom low iron status should be one of the factors determining the intensity of planned training. Frequent training sessions characterized by high training loads may result in a persistent inflammatory state, promoting increased hepcidin concentrations. This implies the need for periodization of training volume and intensity, particularly in individuals with low ferritin levels or symptoms of IDNA, and for allowing adequate recovery of iron metabolism. IDNA itself does not require restriction of training; however, it justifies increased awareness of the impact of training intensity and the timing of iron supplementation on the overall status of iron metabolism.

In this context, hypoxic exposure represents an additional physiological stressor that may further interact with iron metabolism beyond the effects of exercise alone.

Interactions between hypoxia and iron metabolism are complex and influenced by multiple factors. Okazaki et al. demonstrated that reduced iron levels in the body may result in a blunted erythropoietic response to hypoxia and may impair improvements in performance following return from altitude training (Okazaki et al., 2019).

In another study, it was demonstrated that hypoxic conditions may positively affect iron absorption, which may be related to a concomitantly lower increase in hepcidin after exercise compared with conditions at sea level (McKay et al., 2024).

However, the study by Koivisto-Mørk et al. conducted in a population of elite athletes provides a broader perspective. Their findings showed that baseline ferritin concentration and iron supplementation were not as important as the overall cumulative hypoxic dose. It should be noted, however, that the participants did not suffer from marked iron deficiency or clinical symptoms of iron deficiency (Koivisto-Mørk et al., 2021).

This suggests that, with appropriate meal timing, dietary composition, and iron supplementation, it may be possible to optimize iron metabolism in athletes without advanced iron deficiency, including potentially those with iron deficiency without anemia (IDNA), during altitude training.

7. Discussion

The available evidence suggests that IDNA is a prevalent condition in athletic populations. Reduced iron stores, even with normal hemoglobin concentrations, may impair aerobic capacity and efficiency of training. In low iron conditions mitochondrial ATP production is reduced. As a consequence, athletes show decreases in VO_2 -based performance and fatigue during endurance exercise. Nonetheless, the influence of IDNA on athletic performance varies between studies and appears to depend on baseline ferritin concentrations, training intensity and sex-specific factors. The performance benefits are most consistent in individuals with very low iron stores ($\leq 20 \mu\text{g/L}$) and in this population supplementation of iron may be advised. Still there is a need for more evidence in the group of male athletes and in team-sport disciplines.

Diagnostic uncertainty remains an important issue. Clinical ferritin cut-offs may underestimate functional deficiency in athletes, prompting the proposal of performance-relevant zones between 30 and 50 $\mu\text{g/L}$, with potential modifications by age, sex and sport. Increasing attention has also been given to hepcidin as a regulator of iron absorption. Exercise- and hypoxia-induced elevations in hepcidin may restrict iron availability and hold practical relevance for the timing of nutritional intake and supplementation, although these strategies are not yet routinely implemented.

Further work is required to clarify the performance consequences of IDNA, particularly through randomised controlled trials, and to investigate mechanistic links between iron status, training adaptation and hypoxic exposure. Little is known about non-performance outcomes such as cognition, immune function or fatigue in athletic cohorts. Establishing standardised diagnostic criteria, screening intervals and individualised management approaches represents an important direction for future research and may ultimately support more precise, evidence-based strategies in athlete monitoring and care.

8. Conclusions

The overall body of evidence indicates the clinical relevance of iron deficiency without anemia (IDNA), particularly in athletic populations. Increased physical activity and the accompanying metabolic stress, compared with the general population, render athletes more susceptible to conditions associated with iron deficiency. This may translate not only into alterations in iron-related laboratory parameters, but also into reduced training performance, diminished ability to achieve sporting goals, and impaired overall well-being.

IDNA carries consequences for different types of physical exercise. In particular, aerobic capacity in athletes shows a significant reduction compared with a state of physiological iron homeostasis. Likewise, the benefits expected to be obtained during altitude training may prove to be unsatisfactory in this population. IDNA itself does not necessarily require training restrictions, but rather encourages modification and adjustment of training according to individual athlete parameters. This is particularly important in populations of athletes who are at the highest risk of developing clinical and performance-related symptoms in the course of iron deficiency, such as endurance athletes, women, and individuals training under hypoxic conditions.

It is worth emphasizing that IDNA is a common condition and may occur without the clinical symptoms typically associated with anemia. Normal hemoglobin values do not exclude the presence of disturbances in iron metabolism and should not be regarded as a decisive parameter. Assessment of iron status should take into account a range of factors, including sex, type of sport discipline, training load, and iron levels in the body, most commonly assessed by serum ferritin concentration. At the same time, the lack of clearly established ferritin thresholds that are relevant from a physical performance perspective highlights the need for further research in athletic populations.

The data presented above indicate that IDNA does not always constitute an indication for supplementation, but rather justifies an approach based on a broader clinical perspective that incorporates the training plan, training load, and nutritional strategies influencing iron availability. Such an approach may promote improved athletic performance, better adaptation to increasing training intensity, and stabilization of iron metabolism.

Conflicts of interest: No conflicts of interest to declare.

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