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REVIEW ARTICLE

Cardiovascular, respiratory, and metabolic adaptations in amateur Ironman training – a narrative review

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Abstract

Introduction and Objective. Ironman triathlon is an ultra-endurance discipline requiring prolonged high-intensity exercise and substantial physiological adaptation. The aim of this narrative review is to summarise current evidence regarding cardiovascular, respiratory, and metabolic adaptations associated with long-term Ironman training in amateur athletes.
Review Methods. A narrative review of the literature published between 2015–2026 was conducted using PubMed and Scopus databases. Studies concerning cardiovascular, respiratory, metabolic, and body composition adaptations associated with prolonged endurance exercise were included.
Brief description of the state of knowledge. Ironman training induces significant systemic adaptations, including increased VO2max, enhanced ventilatory efficiency, improved respiratory muscle endurance, favourable metabolic adaptations, and physiological cardiac remodelling referred to as 'athlete's heart'. However, chronic excessive endurance exercise may also contribute to adverse outcomes, including myocardial fibrosis, arrhythmias, airway dysfunction, and prolonged physiological stress in susceptible individuals.
Summary. Long-term Ironman training is associated with substantial cardiovascular, respiratory, and metabolic benefits. Nevertheless, excessive training volume and intensity may contribute to adverse physiological consequences. Appropriate balancing of training load and recovery appears essential for optimising performance while minimising long-term health risk.

Key words

endurance training, cardiac remodeling, VO_2max, training load, Ironman triathlon, respiratory adaptations

INTRODUCTION AND OBJECTIVE

Since its origin in 1978 with just 14 participants, the Ironman triathlon has evolved into a globally recognized ultra-endurance event, with its popularity influenced not only by the development of sport itself, but also by broader social and cultural factors, including changing perceptions of health, physical activity, obesity, and athletic identity [1].

The Ironman triathlon represents an endurance-based discipline, particularly in middle- and long-distance formats. Among the most widely recognized formats are the Half-Ironman, consisting of a 1.9 km swim, a 90 km cycling segment, and a 21 km run; and the full Ironman, featuring a 3.8 km swim, 180 km of cycling, and a 42 km marathon run. The Ultraman triathlon, represents an even more demanding ultra-endurance format, comprising a 10 km swim, 421 km of cycling, and an 84 km run, performed predominantly under aerobic conditions [2].

Amateur athletes typically complete middle-distance events within approximately 5–6.5 hours and long-distance races within 10–16 hours. These events require prolonged endurance under variable environmental and terrain conditions, imposing substantial physiological, metabolic and psychological demands. Moreover, athletes face difficulties connected with energy, nutrition, and hydration management to complete the distance. Therefore, successful participation requires highly specific training supported by a well-developed aerobic capacity in both recreational and elite athletes [3].

During these competitions, athletes are required to sustain submaximal intensity over prolonged periods in order to delay the onset of fatigue and exhaustion. Although substantial knowledge exists regarding training practices and competition participation among recreational athletes aged 20–35, less attention has been given to the specific demands placed on different age-group triathletes striving to achieve qualifying times for the Ironman World Championship [3].

The aim of this narrative review is to summarise current evidence regarding cardiovascular, respiratory, and metabolic adaptations associated with prolonged Ironman training and participation in amateur endurance athletes. Emphasis is placed on training characteristics, cardio-respiratory fitness, myocardial remodelling, metabolic adaptations, body composition, and potential adverse consequences associated with chronic excessive endurance exercise.

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REVIEW METHODS

A narrative review of the literature published between 2015–2026 was conducted using the PubMed and Scopus electronic databases. The literature search included the following key words: 'Ironman triathlon', 'endurance training', 'VO_2max', 'athlete's heart', 'cardiac remodelling', 'respiratory adaptations', and 'metabolic adaptations'. Original studies, review articles, and clinical investigations concerning cardiovascular, respiratory, and metabolic adaptations associated with prolonged endurance exercise were included. Publications unrelated to endurance athletes, conference abstracts, and non-English-language articles were excluded. The review focused primarily on amateur and elite athletes participating in long-distance triathlon events. Studies were selected based on their relevance to the objectives of this narrative review after title, abstract, and full-text evaluation. Because this is a narrative review, no formal quality assessment or risk-of-bias analysis was performed. The included studies differed substantially regarding methodology, participant characteristics, and training status, which may limit direct comparison of findings. Furthermore, the predominance of observational studies and the heterogeneity of the available evidence should be considered when interpreting the presented findings.

DESCRIPTION OF THE STATE OF KNOWLEDGE

Characteristics of Ironman triathlon training and competition. An Ironman triathlon is an ultra-endurance race consisting of a 3.86 km swim, followed by a 180.26 km cycling segment, and concluding with a 42.195 km marathon run, resulting in a total distance of 226.3 km [4]. To compete successfully in this event, triathletes must undertake a substantially greater training volume compared with athletes specializing in a single discipline, as they are required to prepare simultaneously for swimming, cycling, and running [5].

The primary objective of training is to optimize competition performance; however, training strategies must be individualized regarding frequency, volume, and intensity. Imbalances between training load and recovery may lead to fatigue, overtraining syndrome, injury, or illness. Consequently, well-designed training programmes should maximise performance while minimising these risks [6].

Typically, athletes perform two daily training sessions that differ considerably in structure and movement patterns, thereby placing substantial demands on the entire body. Individuals beginning triathlon training usually engage in approximately 5–6 sessions per week [7]. Although training frequency varies across different phases of the season, elite triathletes commonly exceed 20 hours of weekly training, whereas amateur triathletes generally complete approximately 12 hours per week [8, 9]. Interestingly, high training volumes (>20 h per week) performed within 40 days prior to competition among amateur athletes, do not necessarily confer additional performance benefits compared with lower-volume training programmes [8, 9].

The annual training cycle of an athlete competing regularly is generally divided into 4 phases: preparatory, base, competitive, and recovery periods. The preparatory phase typically lasts 4–5 months, followed by a 3–4-month base phase, an approximately 3 month competitive phase, and a recovery phase lasting around 2 months. Nevertheless, the duration of each phase may vary depending on the athlete's goals, level of performance, and competition schedule [7,10].

Ironman athletes demonstrate substantial training demands characterised by high weekly training volumes and considerable overall training load. However, the relationship between training load and training time suggests a relatively balanced distribution between volume and intensity [9]. Existing studies provide contrasting findings regarding optimal training intensity distribution in triathlon performance. Some investigations indicate that a greater proportion of low-intensity training is positively associated with endurance performance, whereas excessive amounts of moderate- and high-intensity exercise may impair recovery and adaptation, thereby supporting predominantly low-intensity training approaches [9,11]. In contrast, other studies report that increased time spent performing moderate-intensity training is associated with improved Half-Ironman performance and greater physiological capacity at higher intensities [12].

Collectively, these findings confirm that overall training volume remains one of the most important determinants of endurance performance. However, the optimal distribution of training intensity remains unclear, and further research is required to better understand the relationship between low-, moderate-, and high-intensity training in triathlon athletes. Ironman athletes are exposed to exceptionally high levels of physical exertion not only during competition, but also throughout prolonged training periods aimed at improving athletic performance. Consequently, the balance between training volume, exercise intensity, and recovery plays a crucial role in determining physiological adaptation and long-term athletic health. In addition to training-related performance adaptations, prolonged endurance exercise also induces substantial respiratory, cardiovascular, and metabolic changes.

Ironman training and respiratory fitness. The health benefits of regular physical activity are well established. Individuals who engage in systematic exercise demonstrate a more favourable cardiovascular risk profile, lower blood pressure, increased bone and skeletal muscle mass, improved psychological well-being, and reduced risk of coronary artery disease and myocardial infarction [13–15].

Physiological indicators, such as maximal oxygen uptake VO_2max, ventilatory thresholds, and lactate dynamics, represent key determinants of triathlon performance and vary throughout different phases of the training cycle [16]. Maximal oxygen uptake (VO_2max), achieved during graded exercise testing to exhaustion, is widely recognized as one of the most reliable indicators of cardiorespiratory fitness and aerobic capacity [16–18]. VO_2max reflects the maximal rate of oxygen uptake despite increasing workload and may be expressed in absolute terms (L/min) or relative to body mass (mL/kg/min) [19]. In healthy individuals, VO_2max values typically range between 15 – 85 ml/kg/min. Values exceeding 50 ml/kg/min are generally associated with highly trained individuals, whereas levels above 70 ml/kg/min are most frequently observed in elite endurance athletes competing at an international level [20].

Endurance training significantly improves VO_2max, particularly among individuals with lower baseline fitness levels and during prolonged training interventions, highlighting the effectiveness of endurance exercise for enhancing aerobic performance [21,22]. However, although cardiorespiratory fitness is a strong predictor of endurance performance, the ability to sustain exercise intensity near the lactate threshold may represent a more reliable determinant than VO_2max alone, as endurance performance is influenced by multiple physiological and biomechanical factors [23]. These factors include age, gender, training status, biomechanics, and exercise economy, all of which may substantially influence competition outcomes [16].

Ironman preparation induces significant respiratory adaptations, including improved ventilatory capacity, enhanced respiratory muscle endurance, and greater gas exchange efficiency, all of which support sustained high ventilation during prolonged exercise [24]. Respiratory muscles involved in endurance exercise demonstrate remarkable resistance to fatigue, high oxidative capacity, and efficient distribution of ventilatory workload across multiple muscle groups, thereby enabling prolonged and effective breathing during ultra-endurance activity [25]. Respiratory muscle strength, particularly maximal expiratory pressure and diaphragmatic function, has been shown to correlate strongly with aerobic parameters, such as VO_2max, suggesting that targeted respiratory muscle training may further enhance endurance performance [25,26].

In contrast, pulmonary structure and diffusion capacity appear to demonstrate relatively limited adaptive changes in response to endurance training, even among elite athletes. This disparity suggests that oxygen demand during exercise is driven primarily by highly adaptable cardiovascular and skeletal muscle systems, whereas the pulmonary system relies on an inherent physiological reserve. Consequently, the respiratory system may become a limiting factor for oxygen transport under extreme exercise conditions [25].

However, despite these favourable adaptations, prolonged exposure to sustained high ventilation may also contribute to adverse respiratory outcomes. Ironman athletes may be at increased risk of exercise-induced bronchoconstriction, airway inflammation and oxidative stress, even in individuals without a prior diagnosis of asthma [15,27]. Repeated exposure to environmental irritants, dry air, chlorinated water, and prolonged hyperventilation may further exacerbate airway dysfunction in susceptible athletes.

Overall, Ironman training exerts predominantly beneficial effects on respiratory fitness and aerobic performance. However, prolonged exposure to extreme endurance exercise may increase susceptibility to respiratory complications in selected individuals.

It should be noted that most available studies included relatively small cohorts and heterogeneous assessment methods, limiting direct comparison of results.

Myocardial adaptations to Ironman triathlon training. In addition to respiratory adaptations, prolonged endurance exercise also induces substantial structural and functional changes within the cardiovascular system. Regular moderate physical activity is highly effective in the prevention and treatment of numerous chronic diseases and is associated with improved cardiovascular health and increased life expectancy. However, prolonged excessive endurance exercise may also induce pathological structural remodelling of the heart in selected individuals [28]. Regular physical exercise induces mild left ventricular hypertrophy, which is generally considered a physiological adaptive response to repetitive exercise-related stress [29]. Exercise-induced cardiac remodelling encompasses the structural, functional and electrophysiological adaptations of the heart in response to the metabolic and hemodynamic demands of exercise [30]. These adaptations are collectively referred to as the 'athlete`s heart' [31].

Cardiac remodelling associated with endurance training includes adaptive modifications in chamber size, myocardial wall thickness, and cardiac function, thereby enabling the heart to tolerate the substantial hemodynamic demands generated during prolonged exercise [32]. Compared with the general population, endurance athletes exhibit increased left ventricular mass, myocardial wall thickness, and atrial dimensions, reflecting predominantly physiological adaptation to long-term endurance training [33]. Expansion of the cellular myocardial compartment accompanies these structural changes and appears to correlate with increasing cardiorespiratory fitness [34]. Both the left and right ventricles are exposed to substantial haemodynamic stress during prolonged endurance exercise. Although these changes are generally considered physiological, disproportionate right ventricular remodelling has been associated with atrial arrythmias in a subset of highly trained endurance athletes [25,35]. Enlargement of both atria is likewise regarded as a normal adaptation to chronic endurance training [36]. Female athletes demonstrate similar adaptations, although cardiac dimensions are generally smaller than in males [37]. Electrocardiographic adaptations associated with endurance training include sinus bradycardia, lower resting heart rate, and voltage criteria consistent with physiological left ventricular hypertrophy [38–40]. Approximately 85% of athletes demonstrated at least one training-related electrocardiographic adaptation after six months of Ironman preparation [40]. Female athletes generally present less pronounced electrocardiographic changes than males [41].

Despite these physiological adaptations, some authors suggest that prolonged and high-intensity endurance exercise may contribute to myocardial fibrosis, myocardial inflammation, oxidative stress, and conduction abnormalities [15,32,42]. These alterations appear particularly pronounced within the atria, interventricular septum, and right ventricle, and may increase susceptibility to atrial and ventricular arrhythmias, including atrial fibrillation [15,42]. Additionally, chronic excessive endurance exercise may be associated with increased coronary artery calcification, although current evidence suggests that endurance athletes are not necessarily more likely to develop high-risk atherosclerosis plaques than sedentary individuals [43]. It has also been proposed that prolonged excessive exercise may contribute to increased arterial stiffness [42,44]. Furthermore, elevated concentrations of circulating biomarkers reflecting exercise-induced myocardial damage have been observed following prolonged endurance events [32,45].

Despite extensive investigation, myocardial adaptations associated with the athlete's heart remain incompletely understood. Distinguishing physiological cardiac remodelling from pathological hypertrophy may be particularly challenging in borderline cases [34]. Moreover, most available evidence is derived from observational studies, and the long-term clinical significance of some reported cardiac abnormalities remain uncertain. Overall, endurance training remains highly beneficial for cardiovascular health; however, excessive long-term training loads may contribute to adverse cardiac remodelling in susceptible individuals.

Metabolic adaptations in amateur Ironman athletes. Maximal fat oxidation has been shown to be significantly associated with Ironman performance, indicating that enhanced lipid utilization during prolonged exercise contributes substantially to ultra-endurance capacity. One of the key findings reported in endurance-trained triathletes was a significantly higher VO_2max compared with healthy active controls, reflecting superior aerobic capacity and metabolic adaptation to endurance exercise [46]. Triathletes additionally demonstrated elevated intramyocellular lipid levels, faster phosphocreatine (PCr) resynthesis during post-exercise recovery, shorter PCr recovery time constants (τPCr), and greater maximal oxidative capacity. Multivariate regression analyses revealed that phosphodiester concentration represented one of the strongest independent predictors of VO_2max [47]. These findings suggest that endurance-trained athletes exhibit highly efficient mitochondrial oxidative metabolism and improved skeletal muscle energy turnover. In addition to enhanced oxidative metabolism, prolonged endurance exercise induces substantial hormonal, inflammatory, and haematological responses associated with physiological stress and post-exercise recovery.

Recent studies have demonstrated significant elevations in cardiac and skeletal muscle biomarkers following intense endurance exercise. Biomarker responses increase after triathlon participation across all race distances, with greater elevations generally observed following longer events, particularly for creatine kinase, myoglobin, and lactate dehydrogenase. In contrast, cardiac troponin T often remains unchanged. Furthermore, cortisol and free fatty acid concentrations increase after competition, especially following longer-distance races, indicating substantial physiological stress and enhanced lipid mobilization [48].

Physical exertion significantly influences plasma volume regulation. During prolonged exercise, plasma volume may decrease due to sweating and fluid redistribution, whereas post-exercise recovery is commonly associated with plasma volume expansion resulting from fluid intake, reduced renal sodium excretion, and movement of fluid from interstitial tissues into the vascular compartment. Intense endurance exercise may additionally induce exercise-related rhabdomyolysis, leading to the release of skeletal muscle breakdown products that may contribute to transient organ stress, particularly affecting renal function [48].

Although some investigations report no major alterations in haematological parameters following endurance events, other studies demonstrate substantial exercise-induced haematological changes associated with Ironman participation. Significant temporal alterations have been observed in white blood cell count, platelet count, red blood cell count, haemoglobin concentration, haematocrit, and mean corpuscular volume [49].

Immediately following competition, increases in white blood cells and platelets are commonly reported, whereas reductions in red blood cells, haemoglobin, haematocrit, and mean corpuscular volume are frequently observed during the recovery period approximately 16 hours post-race. These changes may result from exercise-induced haemolysis associated with elevated body temperature, hypoglycaemia, iron loss, oxidative stress, and repetitive mechanical trauma during prolonged running [49].

Participation in ultra-endurance events has also been associated with reductions in body mass and fat mass, increased relative body water content, and marked elevations in biomarkers reflecting muscle damage and physiological stress, including creatine kinase, C-reactive protein, aldosterone, and cortisol. Simultaneously, reductions in testosterone concentration have been observed, indicating significant metabolic, hormonal, and inflammatory responses to prolonged endurance exercise [50].

In endurance athletes, particularly long-distance triathletes and runners, aerobic energy systems play a dominant role in sustaining performance. Nevertheless, balanced development of both aerobic and anaerobic metabolic pathways remains essential for optimizing exercise recovery and long-term training adaptation [51].

Ironman triathletes demonstrate anthropometric characteristics broadly similar to those observed in endurance runners, with lower body fat levels strongly associated with improved athletic performance. However, compared with runners, triathletes generally exhibit relatively greater body mass and body mass index (BMI). High-level triathletes typically present low body fat percentages of approximately 11%, whereas increased body fat is associated with reduced running economy, lower VO_2max, and impaired endurance performance. Although the health and aerobic benefits of endurance sports are well established, body composition additionally represents an important determinant of Ironman performance [52].

Somatotype appears to significantly influence race outcomes in male athletes, accounting for approximately 28.6% of variance in overall race time. Lower endomorphy and greater ectomorphy are associated with superior performance, particularly during the running discipline, followed by cycling and, to a lesser extent, swimming [52].

Peak Ironman performance occurs at a similar age range in both men and women, generally between 32 – 33 years. Furthermore, the performance gap between genders has progressively decreased over time, suggesting increasing competitive potential among elite female athletes. Body composition is closely associated with endurance performance because excessive adipose tissue negatively influences movement efficiency and increases energetic cost, whereas fat-free mass supports exercise performance and muscular endurance [53].

Throughout the training season, gradual reductions in body mass and fat-free mass may occur, while biomarkers such as cortisol, testosterone, and immune-related parameters generally demonstrate only minor fluctuations in male athletes. Following the competitive phase, training volume typically decreases, fat-free mass may remain below baseline levels, free cortisol concentrations increase, and both total and free testosterone levels decline [54].

In a cohort of 61 male Ironman athletes, higher VO_2max and greater maximal fat oxidation were independently associated with faster race times, whereas greater body fat percentage was associated with poorer performance. Together, VO_2max and MFO explained approximately 50% of variability in race outcomes, indicating that both aerobic fitness and fat utilization represent major determinants of ultra-endurance performance [46]. Additionally, increased total and regional body fat, including greater skinfold thickness, has been negatively associated with VO_2max and ventilatory thresholds. Abdominal and trunk adiposity appear to demonstrate the strongest inverse relationship with aerobic performance capacity [49, 55].

Differences in study design, nutritional protocols, and race characteristics may partly explain inconsistencies reported between studies.

Comparison of metabolic parameters with the general population. Regular physical activity plays a crucial role in preventing cardiovascular disease, reducing mortality risk, improving metabolic health, and supporting body weight regulation. Moreover, exercise serves as an effective therapeutic and rehabilitative intervention in numerous chronic diseases [56].

Compared with sedentary individuals, endurance athletes generally demonstrate superior aerobic capacity, greater metabolic flexibility, and more favourable cardiovascular and body composition profiles. Selected physiological and metabolic differences between amateur Ironman athletes and the general population are summarized in Table 1.

Table 1. Comparison of selected physiological and metabolic parameters between amateur Ironman athletes and the general population

Parameter	Amateur Ironman Athletes	General Population
VO_2max	Significantly increased	Lower values
Resting heart rate	Reduced	Higher
Insulin sensitivity	Improved	Lower
Body fat percentage	Lower	Higher
Mitochondrial oxidative capacity	Enhanced	Lower
Lipid metabolism	Greater fat oxidation efficiency	Lower metabolic flexibility
Endothelial function	Improved	Less efficient

Nevertheless, despite these substantial physiological benefits, chronic exposure to excessive endurance training may also contribute to increased physiological stress and, in selected individuals, adverse cardiovascular or respiratory adaptations.

Although long-term endurance training is associated with numerous beneficial physiological adaptations, excessive training volume and prolonged exposure to high-intensity exercise may also contribute to potentially adverse cardiovascular, respiratory, and metabolic consequences in susceptible individuals. The major beneficial adaptations and potential adverse effects associated with long-term Ironman training are summarized in Table 2.

Limitations of the study. This review has several limitations that should be acknowledged. First, the analyzed studies differed substantially in methodology, participant characteristics, and training status, which may limit direct comparison of findings. Second, a considerable proportion of the available literature focused predominantly on male athletes, resulting in limited data regarding female Ironman participants. Finally, because this study represents a narrative review rather than a systematic review or meta-analysis, the selection of studies may be associated with potential selection bias. Furthermore, most available evidence originates from observational studies with relatively small sample sizes, whereas long-term prospective and randomized studies remain limited.

Table 2. Major beneficial adaptations and potential adverse effects associated with long-term Ironman training

Beneficial adaptations	Potential adverse effects
Increased VO_2max and aerobic capacity	Myocardial fibrosis
Enhanced ventilatory and mitochondrial efficiency	Exercise-induced bronchoconstriction
Improved lipid metabolism and fat oxidation	Chronic physiological stress
Lower resting heart rate and improved cardiac output	Atrial fibrillation and arrhythmias
Physiological cardiac remodelling ('athlete's heart')	Excessive cardiac remodelling
Improved endothelial function and capillarization	Coronary artery calcification
Lower body fat percentage and improved body composition	Hormonal disturbances
Enhanced endurance performance	Overuse injuries and prolonged recovery

Practical and clinical implications. The findings summarized in this review highlight the importance of appropriately balancing training volume, intensity, and recovery in amateur Ironman athletes. Regular endurance training may provide substantial cardiovascular and metabolic benefits, although excessive training loads may contribute to adverse cardiac and respiratory adaptations in susceptible individuals. Therefore, periodic cardiovascular evaluation, individualized training strategies, and appropriate recovery protocols may help optimize athletic performance while minimizing potential long-term health risks.

SUMMARY

Ironman triathlon training induces substantial cardiovascular, respiratory, and metabolic adaptations that enable athletes to tolerate prolonged ultra-endurance exercise. Compared with the general population, amateur Ironman athletes demonstrate superior aerobic capacity, metabolic flexibility, and cardiovascular efficiency. However, chronic excessive endurance training may also contribute to adverse cardiac and respiratory adaptations in susceptible individuals. Although the reviewed evidence consistently demonstrates beneficial physiological adaptations, interpretation of current findings should be undertaken cautiously because of methodological heterogeneity and the predominance of observational studies. Overall, appropriately balanced endurance exercise remains highly beneficial for general health and cardiovascular function.

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