Nutrition for iron-distance triathletes: an overview and some practical advice

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OVERVIEW

Ironman® triathlons are ultra-endurance events which take competitors between 7 hours 35 minutes and 17 hours to complete. These events continue to grow in popularity, but although the importance of nutrition to support training and facilitate performance is acknowledged, information is often contradictory and can result in triathletes inadvertently compromising training, health and performance. The aim of this article is to give an evidence-informed overview of nutrition and to provide practical advice for iron-distance triathletes and their coaches.

Introduction

Ironman® or iron-distance triathlons are ultra-endurance events, consisting of a 3.8 km (2.4 mile) open-water swim, 180 km (112 mile) cycle ride and 42.2 km (26.2 mile) run.[73] Participants vary widely in ability, with finishing times ranging from 7 hours 35 minutes to 17 hours.[51] Competing in these events requires considerable preparation and a high training load, with reported weekly training volumes of 12 hours for recreational athletes to over 30 hours for elite athletes.[57] Performance decrements related to inadequate energy consumption and/or dehydration are prevalent in iron-distance events,[51] and as such, nutrition is often referred to as the fourth discipline in a triathlon.

Physiological demands

Endurance performance is physiologically determined by an athlete's rate of maximal oxygen consumption ($\dot{V}O_2max$), the proportion of $\dot{V}O_2max$ they can sustain (related to lactate turnpoint) and their exercise economy.[11] Blood lactate concentrations, glycogen utilisation and time to fatigue can display a twofold difference at the same absolute workload in individuals with a similar $\dot{V}O_2max$, suggesting that factors which control muscle glycogenolysis and blood lactate concentrations can affect endurance performance.[19] The goal of training for an iron-distance event is inevitably to improve these variables and in recent years, research has demonstrated that endurance training adaptations can be augmented through strategic manipulation of nutritional status.[13]

During prolonged exercise, carbohydrate (CHO) and fat are the primary substrates oxidised for energy metabolism.[79] The oxidation rates of these substrates are determined by numerous factors including intensity and duration of the exercise, glycogen concentrations and environmental conditions.[71,84] Glycogen is stored primarily in the muscle (~80–85%) and liver (~15–20%) with small amounts circulating in blood.[3] Training status improves absolute glycogen storage capability, but even in highly trained athletes, total glycogen storage amounts to <3000 kcal (<740 g); in contrast, even in very lean

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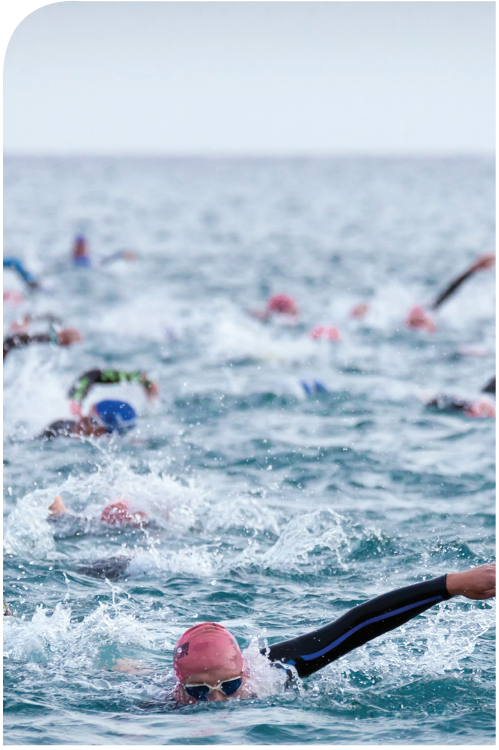

individuals, fat storage can amount to ~68,250 kcal (7000 g).[26]

The most important substrate at moderate to high exercise intensity (>70% $\dot{V}O_2$max) is CHO, due to its greater energy yield per litre of oxygen consumption (5.01 vs. 4.85 kcal·L^{-1} O2 for CHO and fat respectively) and higher rate of ATP resynthesis.[46] Using doubly labelled water, it has been estimated that energy expenditure for an iron-distance triathlon may range from 8,500-11,500 kcal,[20,47] and that elite triathletes have an energy expenditure rate of ~20.1 kcal·min^{-1}.[57] Relative contribution of fat to total energy needs is intensity dependent with maximal fat oxidation usually occurring around 59-64% $\dot{V}O_2$max in endurance trained athletes.[1] This corresponds to fat oxidation rates of 0.6 to 1 g·min^{-1}, although values of 1.5 g·min^{-1} have been reported (in habitual very low CHO/ketogenic athletes).[25] Professional iron-distance triathletes compete at intensities of ~66-71% $\dot{V}O_2$max,[61] and therefore it is clear that fat oxidation alone cannot provide energy at a sufficient rate. Additionally, as core body temperature increases, proportionally more CHO is oxidised, further reducing the amount of energy provided by fat oxidation.[72] Endurance training improves capacity for fat oxidation[63] and fat oxidation proportionally increases as exercise intensity decreases, yet even slower finishers (~13 h) require 875 to 1999 g of CHO to complete an iron-distance triathlon.[57] In addition to its role as an energy substrate, glycogen acts as a regulatory molecule that modulates selected skeletal muscle markers of training adaptation.[30] Performing some training sessions with low glycogen concentrations ('train-low') can increase training adaptations; it is therefore important to distinguish between CHO needs for racing and for training.[37]

Fatigue during iron-distance events is associated with muscle glycogen depletion, reduced blood glucose concentrations and dehydration.[41] Glycogen becomes depleted after 2-3 hours of moderate to high-intensity exercise (>70% $\dot{V}O_2$max); it is therefore important that iron-distance triathletes should seek to maintain glycogen stores through training strategies that augment fat oxidation as well as consumption of exogenous CHO during races,[57] while maintaining appropriate hydration status. In addition to fatigue, performance is often compromised by high reported incidences of gastrointestinal (GI) issues.[43]

Aims

Few studies have explored nutritional practices in iron-distance triathlon and recommendations for race fuelling have not always differentiated between the needs of elite and recreational triathletes. Little attention has been paid to nutritional support during training and manipulating glycogen status to enhance training adaptations. The aim of this article is to provide iron-distance triathletes with nutritional recommendations for both training and racing.

Nutritional requirements

Physiological demands of iron-distance training and competition are extremely high.[48] Nutritional recommendations should be aimed at maximising training adaptation and performance, by ensuring CHO, protein, fat, hydration and micronutrient needs are met. Factors that affect gut health should also be considered because of the high incidence of GI issues in iron-distance races.

Carbohydrates

Since the beginning of the 20th century, exercise physiology research has clearly demonstrated ergogenic benefits of high CHO diets;[50] and in the 1960s, muscle biopsies linked the improved performance to elevated muscle glycogen content.[12] The evidence that exercise performance is improved by high CHO availability led to nutritional recommendations that endurance athletes consume high CHO diets before, during, and after training sessions.[14] In recent years however, evidence has accumulated for deliberately undertaking some training sessions with low glycogen concentrations (termed 'train-low') to augment endurance training adaptation;[37] it is therefore important to distinguish between CHO needs for competition and those for training.

CARBOHYDRATES FOR TRAINING

Daily CHO recommendations for endurance athletes who train at a moderate to high intensity for 1 to 3 hours a day are 6-10 $g \cdot kg^{-1}$ body mass (BM), and for those who train for over 4 hours a day they are 8-12 $g \cdot kg^{-1}$BM.[14] There are no available data on nutritional intakes of elite iron-distance triathletes, but data on good age-group triathletes (including Ironman® 70.3 World Championship qualifiers) have shown daily CHO intakes of 7 $g \cdot kg^{-1}$BM with a training volume of ~17 h per week.[55]

Despite the importance of nutrition for endurance performance and the complexity of nutritional recommendations, the use of nutrition professionals is uncommon among triathletes and nutrition information is predominantly sourced from the Internet, other athletes and coaches.[49] Chronic low-CHO, high-fat (LCHF) diets are currently popular and are promoted in social media as a method of improving endurance performance through improved fat oxidation and concurrent weight loss, but there is limited support for this dietary approach in the scientific literature. Studies reporting benefits have shown improvements in only submaximal exercise capacity,[85] which does not necessarily relate to race performance.

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Table 1. Example of CHO periodisation for an elite iron-distance triathlete

	PRE-AM WORKOUT	DURING AM WORKOUT	POST-AM WORKOUT	LUNCH	PRE-PM WORKOUT AFTERNOON/SNACKS	DURING PM WORKOUT	POST-PM WORKOUT/ EVENING MEAL
Day 1 (easy day, fuel according to needs) AM: 1h easy swim PM: 1h gym mobility	LOW	LOW	MEDIUM	LOW	MEDIUM	LOW	MEDIUM
Day 2 (train-high, sleep-low). AM: 2h threshold ride. PM: 2h run at race pace	HIGH	HIGH	HIGH	HIGH	HIGH	MEDIUM	LOW
Day 3 (train-low) AM: 4hr easy bike	LOW	LOW	HIGH	HIGH	HIGH	N/A	MEDIUM
Day 4 (train-high, sleep-low). AM: 1h 30 swim with threshold intervals PM: 2h VO_2max ride	HIGH	HIGH	HIGH	HIGH	HIGH	LOW	LOW

This model is presented for a high-level triathlete, who mostly trains twice a day on four consecutive days. The CHO content of each feeding point is represented as low, medium or high. Specific amounts of CHO will be dictated by athlete history, specific training goals, training status, phase of training etc and the use of a colour scheme – rather than absolute quantities – highlights the necessity for an individualised, flexible approach. Models should be adjusted daily according to the number of feeding points and training sessions.[38]

Prospective examination of nutritional intentions of long-distance triathletes demonstrated that more than half of them planned to reduce their CHO intake despite increasing volume or intensity of training during the forthcoming season.[49] It is likely that athletes and coaches are misunderstanding the 'train-low' concept and believe that benefits are achieved through prolonged periods of CHO restriction, while in reality certain sessions are strategically targeted as 'train-low' and the overall training programme is supported by a high CHO diet.[66]

Elite iron-distance triathletes have weekly training volumes of 20 to >30 hours and need to maximise their ability to use exogenous CHO and glycogen stores as fuels in order to support energy requirements for training and racing.[41,57] The use of a periodised CHO strategy to augment fat oxidation and preserve endogenous glycogen stores, while maximising the absolute capacity for exogenous CHO oxidation, should be employed.[29]

Training low

Commencing endurance training sessions with low muscle glycogen concentrations (<300 mmol·kg^{-1}dw)[38] has been shown to enhance training adaptation through increased mitochondrial enzyme activity and mitochondrial content,[80] as well as increasing rates of fat oxidation.[4,36] 'Training-low' can be achieved by acute strategies including post-exercise CHO restriction, training twice per day with the second session commenced with low glycogen concentrations, and fasted training where exercise is performed before breakfast so liver glycogen and blood glucose concentrations are reduced.[9,28] Prolonging the duration of low glycogen concentrations can extend and enhance the activation of molecular pathways that regulate skeletal muscle adaptation. A common method is a 'sleep-low, train-low' protocol involving a glycogen depleting evening training session, CHO restriction overnight and a fasted training session the following morning.[37] 'Sleep-low, train-low' protocols have been shown to enhance training adaptations[10,60,86] and improve performance by 3 to 7%.[53,54]

Training high

Maintaining a high quality of training is imperative for long-term adaptation.[13] Commencing sessions with high CHO availability (through repletion of endogenous stores and supplementation of exogenous CHO during exercise) improves exercise capacity and performance.[41] Regardless of the capacity to oxidise fat, as exercise intensity increases above 75-80% $\dot{V}O_2$max there is a rise in adrenaline and a shift to CHO metabolism.[66] Any key sessions that are >75 min and contain moderate to high-intensity efforts (>70% $\dot{V}O_2$max) should be commenced with high CHO availability.[13] Additionally, training with high levels of exogenous CHO helps 'train the gut' and can reduce the incidence and severity of GI symptoms. Athletes should follow the CHO guidelines for performance, outlined below, to ensure high CHO availability in these sessions.

Application of periodised nutrition
Periodised nutrition requires clear planning. To optimise glycogen re-synthesis, athletes should consume 1.2 g·kg-1BM of CHO immediately after training and every hour for the next four hours.[15] High glycaemic index (>70) CHO is preferable as this maximises re-synthesis rates. The inclusion of fructose along with glucose may help facilitate liver glycogen synthesis due to differing mechanisms of absorption and because fructose is preferentially metabolised by the liver.[26] Ingesting CHO in liquid as opposed to solid form does not affect glycogen re-synthesis rates and a sports drink can be useful if appetite is suppressed, as well as having the added advantage of helping to restore fluid balance.[42] For the rest of the day, athletes should include high CHO choices in their meals and snacks to ensure adequate energy and substrate availability for glycogen re-synthesis. On these days, athletes should aim for 8-12 $g \cdot kg^{-1}$BM of CHO. When there is a period of more than 24 hours between training sessions, maximising glycogen re-synthesis in the post-exercise period is not a priority, and athletes consuming a high CHO diet will replenish glycogen by the next session.[66]

If exercise intensity has been low/moderate (<65% $\dot{V}O_2$max) or the session included only short bouts of high-intensity (eg, strength training), fat oxidisation will have provided the majority of energy and moderate CHO intake will suffice.[42] CHO consumption can be kept low following a moderate/hard training session if there is a deliberate decision to commence the subsequent session with low glycogen stores or to extend the period in which adaptive responses are elevated.[66,67] Table 1 shows an example of CHO periodisation.

CARBOHYDRATES FOR PERFORMANCE

Carbohydrate loading
Carbohydrates play an important role in preparing for competition, with intake in the days before competition aimed at maximising muscle glycogen concentrations,[13] and intake in the hours before competition aimed at topping up liver glycogen.[29] Consumption of 8-12 $g \cdot kg^{1}$BM for 36-48 hours prior to an iron-distance event is recommended[81] and, combined with the exercise taper, is sufficient to ensure high muscle glycogen concentrations. Individuals vary in their response to glycogen-loading, and therefore planned strategies should always be practised extensively in training. Food choices in this period should be low in fibre to minimise residue, reducing the need to defecate and the likelihood of GI distress during the event, as well as helping to offset the 1-3% BM gain associated with the storage of additional glycogen/water.[13]

Race morning
Guidelines for the pre-race meal are consumption of 1-4 $g \cdot kg^{-1}$BM of easily digestible CHO, low in fibre, fat and protein, 3-4 hours before the start,[16,81] aimed at topping up liver glycogen.[26] This large range (between 75 and 300g for a 75kg athletes) has implications for practice: for example, a larger meal might need to be eaten 30 minutes earlier (can take longer to eat), especially first thing in the morning, when many athletes are not in the mood to eat such quantities. Triathletes should experiment well in advance of goal races to find out what they can tolerate as a pre-race meal and fine-tune their own strategies,[44] as well as trialling small amounts of CHO in the form of sports drink, gel or similar 15-60 minutes before the start of the event.[70]

CARBOHYDRATE NEEDS DURING IRON-DISTANCE RACES

Endogenous glycogen is insufficient to meet the metabolic demands of iron-distance races, and therefore CHO feeding is necessary to attenuate fatigue and optimise performance.[57] For events lasting longer than 2.5 hours, 90 $g \cdot h^{-1}$ of multiple-transportable sources of CHO are recommended to maximise utilisation and reduce the likelihood of GI distress due to their higher oxidation rates (glucose:fructose 1.5-1.8 $g \cdot min^{-1}$ versus glucose ~0.8-1 $g \cdot min^{-1}$).[81]

Although significant correlations have been reported between CHO intake and faster finishing times in iron-distance races,[64] practically, few athletes can tolerate or are willing to consume 90$g \cdot h^{-1}$ of CHO. Additionally, although maximising CHO intake might be advantageous for faster athletes who have higher rates of energy expenditure, slower athletes can meet a large proportion of their energy needs through fat oxidation.[57] Exogenous CHO oxidation rates can be reduced by 10% in the heat,[40] despite glycogen utilisation being increased, so intake should be adapted according to the conditions. It is possible to mix various CHO sources (liquids, gels and solids) as long as fibre, fat and protein content is low to prevent delays in gastric emptying. Athletes should take care not to increase CHO concentrations by combining CHO sources, eg, consuming CHO gels or bars along with CHO drinks and thereby impacting CHO absorption.[43]

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Although professional cyclists and elite/top age-group triathletes on the cycle leg of an iron-distance triathlon usually meet CHO recommendations, intake is lower during the run leg (and in marathon events) and non-existent on the swim.[64] The proportion of energy provided from fat oxidation increases with exercise duration,[71] partially mitigating the need for CHO. Although intakes of >60 g·h^{-1} CHO are recommended for elite/top age-group triathletes during the run,[64] difficulties ingesting larger volumes of CHO and fluid during running, along with the rising temperatures due to iron-distance marathons usually commencing in the middle of the day should be considered. CHO intake on the run can be a risk factor for GI symptoms, but given the relationship between faster finishing times and higher CHO intake, athletes should attempt to maximise their ability to uptake CHO during this portion of the race by practising race-fuelling strategy during specific training sessions.

Protein requirements

Protein requirements are higher for endurance athletes than the general population (1.2-2.0 versus 0.8 g·kg^{-1}BM),[81] due to increased protein synthesis (to repair damage to myofibrillar proteins and for mitochondrial biogenesis) as well as oxidation during exercise.[65] Nitrogen balance is better maintained when ~0.3-0.4 g·kg^{-1}BM of high-quality protein (high leucine content) is ingested every 3 to 4 hours throughout the day,[2] amounting to ~1.4-2 g·kg^{-1}BM per day. After training, 0.3-0.4 g·kg^{-1}BM of protein should be included to restore nitrogen balance and to maximise glycogen synthesis if CHO intake is inadequate.[23] Consuming 30-40 g of protein before sleep can increase muscle protein synthesis and facilitate recovery.[39] Adequate CHO and energy consumption prior to sleep (and immediately after exercise) ensure that amino acid intake can be used for repair and synthesis rather than being oxidised as an energy source.[70]

Fat requirements

Fat is an important fuel for endurance exercise and some dietary intake in the form of essential fatty acids (EFAs) is necessary for.[81] Most fat is stored as subcutaneous adipose tissue, with 1-2% of total body fat stored in the muscle as intramuscular triacylglycerol (IMTG) and small amounts in blood as plasma fatty acids and triglycerides.[25,83] Leaner athletes usually finish faster in iron-distance events and many triathletes attempt to manipulate their diet in attempts to both reduce body fat and enhance fat oxidation.[48,55] Chronic LCHF diets impair CHO metabolism[66] and there is no association between maximal rate of fat oxidation and race time in an iron-distance race, even among age-group triathletes who would be more likely to benefit from increased fat oxidation rates.[25] High fat diets are therefore not recommended for elite iron-distance triathletes and instead athletes should as a minimum aim to meet health guidelines of daily intakes of 1 g·kg^{-1}, with intake increasing when necessary to meet energy needs when training loads are high. Dietary fats should contain high levels of EFAs, particularly omega-3.[81] A high-quality fish oil supplement (2 g per day) is recommended for most athletes as this might reduce inflammation as well as supporting the immune system and cardiovascular function.[21]

Hydration

Dehydration is a consequence of body water loss due to sweating and through increased respiration over many hours. Dehydration impairs the process of heat dissipation and results in elevated core body temperature and reduced physical and cognitive performance.[56] Through lowered plasma and stroke volume, heart rate increases for the same workload, a condition which is known as cardiovascular drift.[58] Dehydration of more than 2% is widely believed to negatively affect endurance performance, and accompanying perturbations in electrolyte homeostasis have been associated with cramping and hyponatremia.[52] The recommendations that endurance athletes drink enough fluid to avoid more than 2% body weight loss are based on controlled laboratory studies, so translation of findings into the field requires caution. Proper hydration during ultra-endurance exercise requires a body mass loss of 2% (water is generated with fuel oxidation, water bound to glycogen is released during glycogenolysis, and mass is lost from oxidation of endogenous fuel stores), therefore following re-commendations to maintain body mass can result in hyperhydration.[33] Heat exhaustion is most likely to occur during high-intensity exercise.[5] Even the fastest iron-distance triathletes race at only moderate intensities (~66-71% $\dot{V}O_2max$),[61] and serious elevations in core temperature are not typical during ultra-endurance events, even under hot conditions.[82] Furthermore, excessive

Table 2. Micronutrients in which elite Ironman triathletes might be deficient

	ROLES	SYMPTOMS OF DEFICIENCIES	ATHLETES AT RISK	FOOD SOURCES	RNI AND TIMING
Iron	Oxygen transport as haemoglobin and myoglobin; forms cytochromes and metalloenzymes; promotes immune function	Anaemia; fatigue; increased infections	Intense training; training at altitude; menstruating females; restricted energy intake; specific avoidance of red meat; vegetarians; vegans	Liver, kidneys, eggs, red meat, seafood, oysters, bread, legumes, nuts, leafy green vegetables, broccoli, figs, raisins	8 mg males 18 mg females Ingest with Vit C to facilitate absorption. Avoid calcium, tea, coffee, red wine, chocolate
Vitamin D	Increases calcium absorption in gut; promotes bone formation; important for muscle and immune function	Weak bones/stress fracture; sub-optimal muscle function; increased susceptibility to infections; increased injury risk	Train primarily indoors; latitudes > 35th parallel; train early morning/ late evening; aggressive blocking of UVB exposure (eg, clothing, sun screen)	Liver, fish, eggs, fortified dairy products, oils, margarine *major source is by action of sunlight on skin	2000-4000 IU until serum 25(OH)D > 50nmol/L Consume with fat soluble foods
Calcium	Growth, maintenance and repair of bone; muscle contraction; membrane potentials and nerve impulse transmission; blood clotting; regulates enzyme activity	Osteoporosis; osteopenia; osteomalacia; stress fractures; impaired muscle contraction; muscle cramps	Restricted energy intake; disordered eating; specific avoidance of dairy products; vegans	Dairy products; egg yolk; beans; peas; dark green vegetables; cauliflower	1000 mg
Sodium	Maintain fluid balance; active transport mechanism in cell membranes; important for nerve and muscle function	Cramping if mild; hyponatremia is excessively low sodium levels during exercise. Symptoms include bloating, puffiness, weight gain, headache, vomiting, confusion, seizures, loss of consciousness and possibly death. Thought to occur as a result of overhydration rather than sodium losses	High training volumes; training in hot conditions; high sweat rate; high levels of sodium in sweat	Meat, fish, bread, canned food, table salt, sauces, pickles *Sports nutrition products	1500 mg Can vary widely with athletes losing up 1500mg per litre of sweat, at sweat rates of > 2L per hour. Athletes should assess their sodium needs along with their fluid needs.

fluid intakes do not offer protection from serious heat stroke, and should be avoided to prevent potential health consequences of exercise-associated hyponatremia.[62] Cramping during iron-distance races is common and usually associated with a fluid and sodium imbalance, although experimental evidence suggests that altered neuromuscular control, due to greater demands on muscles relative to the current state of training, is a more likely cause.[33] Athletes generally lose between 4 and 8% body mass during an iron-distance race, with the fastest finishers often exhibiting the greatest losses.[78] There is no evidence that magnitude of weight loss is associated with risk of illness in iron-distance triathlons and reductions in body mass may confer a performance advantage.[76]

Athletes should aim to start iron-distance races euhydrated by consuming CHO drinks as part of their CHO loading strategy in the 48 hours before the race and ingesting 400-600 mL of their preferred CHO drink in the 2 hours before the start.[41]

Sweat rates are significantly affected by body weight, exercise intensity and ambient conditions, with sweat rates of over 2 $L \cdot h^{-1}$ reported in hot and humid climates.[6,58] Athletes can assess their sweat rate by weighing themselves undressed before and after training sessions, and accounting for any fluid or fuel consumed during the session and any urine passed;[77] sodium concentration of sweat can be measured at commercial facilities or otherwise estimated.[6] However, the practicality of such actions is questionable. Fluid balance affects

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the composition of excreted sweat, with sweat sodium concentration significantly increased in mild dehydration (2.4%) compared with euhydration.[59] Rate of sweat production is influenced by several factors during exercise, including exercise intensity, ambient conditions, and airflow over the skin.[35,74] Heat acclimation and sodium intake in the days prior to an exercise bout may also influence sweat sodium concentration.[7]

Taking all these factors into account, evidence suggests that iron-distance triathletes should drink water or other hypotonic fluids to quench thirst, that the sodium consumed with typical sports nutrition products during races appears adequate for avoidance of salt-depletion hypohydration,[31,32] and that supplemental sodium is not necessary.[34,77] Rate of fluid absorption is closely related to the CHO content of the drink, with high CHO concentrations compromising fluid delivery. The optimum CHO concentration seems to be in the range of 5-8%, when both fluid and CHO delivery are high.[8]

Hydration strategies during training should vary according to the desired outcome of the session. During some sessions, athletes should practise their race hydration along with their CHO fuelling strategy to maximise their absorption capability.[41] At other times, athletes should train with

Table 3. Overview of nutritional recommendations for elite Ironman triathletes

	RECOMMENDATIONS
General daily requirements to support training	Daily CHO intake of 3-12 $g \cdot kg^{-1}$BM, according to CHO periodisation plan • 3-5 $g \cdot kg^{-1}$BM for rest or light days, or if deliberately withholding CHO • 6-10 $g \cdot kg^{-1}$BM for 1-3 h of moderate to high intensity training • 8-12 $g \cdot kg^{-1}$BM for over 4 h of moderate to high intensity training Protein: 0.3-0.4 $g \cdot kg^{-1}$BM every 3-4h. 30-40 g protein (eg, casein) prior to sleep if daily protein needs have not been met Fat: 1 $g \cdot kg^{-1}$BM. Include 2 g of Omega-3 fatty acids Hydration: Needs vary widely between individuals and according to the environment. Athletes should pay attention to the colour of their urine and presence of thirst on awakening, before consuming any fluid Micronutrients: Aim to eat a varied diet that includes all food groups and meets daily energy requirements. Consult a health professional if inadequate consumption of key micronutrients is suspected
Recovery from races or when maximising glycogen re-synthesis is a priority	CHO: 1.2 $g \cdot kg^{-1}$BM high-GI sources immediately after training and every hour for the next 4 h Protein: 0.3-0.4 $g \cdot kg^{-1}$BM immediately after exercise if CHO recommendations are not met. As per general guidelines thereafter Hydration: 125-150% of fluid deficit in the hours immediately after exercise. Ideally drinks should contain some CHO and electrolytes to facilitate absorption
Prior to race or targeted sessions to practise race fuelling/train-high sessions	8–12 $g \cdot kg^{-1}$BM CHO for 36-48 h prior. Food choices should be low in fibre and fat Hydration should include CHO/electrolyte drinks Probiotic supplementation should be considered if travelling to a race. Glutamine should be considered if hot conditions
Race morning	1-4 $g \cdot kg^{-1}$BM CHO 3-4 h before the start from easily digestible foods that are low in fibre, fat and protein 30 g CHO from sports drink or semi-solid (eg, gel) 15-60 min before the start 400-600 mL fluid sipped in the 2 h before the start
During race	Recommendations vary between individuals and race fuelling should not change from what was practised in key sessions. Athletes should aim for the following amounts of CHO from a mixture of sports drink, gels and solids according to their personal preferences: Bike: 90 $g \cdot h^{-1}$ CHO, 2:1 glucose:fructose sources Run: >60 $g \cdot h^{-1}$ CHO, 2:1 glucose:fructose sources Fluid and electrolytes according to individual sweat rate and sweat sodium content.

inadequate hydration to get used to the increases in heart rate and perceived effort that will likely occur towards the end of an iron-distance triathlon.[34] Following training sessions, athletes should aim to restore euhydration during the recovery period.[75] Strategies should involve consumption of fluid equivalent to 125-150% of the fluid deficit (1.25-1.5 $L \cdot kg^{-1}$BM lost), with CHO according to individual needs and 0.45 $g \cdot L^{-1}$ sodium to maximise absorption and minimise diuresis/urinary losses.[81] To maintain euhydration, athletes should meet their daily fluid needs outside of training (~1.5-3 L depending on environmental condition) by consuming sufficient fluid to avoid an overnight loss in body mass of over 1% and the presence of dark coloured urine and thirst when assessed in the morning.[8,17]

Micronutrients

Exercise stresses many of the metabolic pathways in which micronutrients are required.[81] These are organic (vitamins) and inorganic (minerals) elements required in minute amounts for optimal health, growth and physiological function. Generally, endurance athletes eating a varied diet, with adequate energy availability, meet their micronutrient needs and no supplementation is usually necessary.[16] Single micronutrient supplements are only appropriate for correction of a clinically defined medical reason. Iron-distance triathletes might be at risk of deficiencies in vitamin D (in winter months, at higher latitudes and if skin exposure to sun is less than 30 minutes a day); calcium (athletes who avoid dairy, low energy availability); sodium (particularly in hot conditions or athletes with a high sweat rate/sodium concentration); and iron (menstruating females, during altitude training).[16,24] Causes and symptoms of deficiencies, recommended intakes and food sources are shown in Table 2.

Gut health

The GI system breaks down ingested food into smaller units that can be absorbed. It is an important athletic organ because it is responsible for the delivery of water and nutrients during exercise as well as being instrumental in health, immune function and well-being.[18] During exercise, blood flow to the GI system is reduced and GI motility and absorption are altered. Permeability is also increased, particularly when exercising in the heat.[27] There is emerging evidence that probiotics and glutamine may help to preserve GI integrity, which may improve performance, particularly in hot conditions.[27] Probiotics can also improve the gut microbiota, potentially being beneficial to health and immunity and have been reported to reduce the incidence and severity of travellers' diarrhoea and upper-respiratory tract infections (URTIs).[69] Probiotic supplementation should therefore be considered in the days leading up to travel and competition. The benefits of probiotics are, however, strain-specific, and in some cases may exacerbate symptoms.[18]

Athletes are advised to test glutamine and probiotic supplements outside of races because of wide inter-individual differences in effectiveness, and ensure that all supplements are certified by a recognised third-party batch-testing programme, such as Informed Sport. Aspirin and other non-steroidal anti-inflammatory drugs (NSAIDs) have been shown to increase intestinal permeability and may increase the incidence of GI complaints. The use of NSAIDs should therefore be avoided, particularly in the pre-race period or during training.[22]

Gastrointestinal symptoms are common in many sports, but particularly prevalent in endurance sports, with up to 96% of participants experiencing some GI symptoms and 4-12% of participants reporting moderate or severe symptoms.[68] In one study, 43% of triathletes reported serious GI problems with 7% having to abandon the race.[45] The intestinal tract is highly adaptable and practising race nutrition during training can improve absorption and alleviate some or all GI symptoms.[72]

There is strong evidence that absorption of CHO is limited by the transport capacity of SGLT1 (sodium-dependent glucose transporter) and extrapolations from animal studies, combined with data from humans, suggest that a few days to two weeks of a high CHO diet is sufficient to cause significant increases in the SGLT1 content in the intestinal lumen, thereby enhancing CHO absorption.[43] Gastric emptying is not thought to limit absorption but might be compromised by the combination of high CHO intake, heat and intense exercise.[43] All these factors highlight the importance of 'training the gut' by practising race nutritional strategy in targeted sessions to ensure high rates of CHO and fluid absorption.

TAKE-HOME MESSAGES

- Iron-distance triathletes should clearly differentiate between CHO needs for training and those for racing
- A periodised CHO approach is optimal, whereby 'train-high' and 'train-low' sessions are strategically combined, in line with specific goals of the session
- Athletes should start iron-distance races with high muscle and liver glycogen concentrations, through a high-CHO diet in the preceding days and a high-CHO pre-race breakfast
- Athletes should 'train their gut' by practising their individual race-fuelling strategy in training, in order to maximise their ability to absorb CHO and minimise risk of GI distress
- An awareness of individual fluid and sodium needs is useful, particularly to restore euhydration after training. During iron-distance races, drinking to quench thirst, along with consuming CHO drinks/gels/bars, appears most appropriate for meeting hydration and sodium requirements.

Conclusions

Success in iron-distance races requires a high volume of training. Supporting this with appropriate nutritional interventions will enhance performance by maximising adaptation and facilitating recovery. Targeted training sessions should be used to optimise individual race nutrition and hydration strategies, as there are wide variations in requirements and tolerances among athletes. Training the gut through practising race-fuelling strategies in training is vital to maximise uptake and absorption and reduce GI issues. Many of the suggestions in this article are drawn from endurance/ultra-endurance literature because of the lack of research in elite iron-distance triathletes, and although providing a good starting point, there is a need for further research in this demographic. A summary of key recommendations is presented in Table 3.

AUTHOR'S BIOGRAPHY

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Sally is a lecturer in sports therapy at the University of Essex and a tutor on the IOPN graduate diploma in performance nutrition. She has been involved in the triathlon for many years, and completed seven Ironman 70.3 races and six Ironman races, podiuming in her age group and qualifying for World Championships on numerous occasions. As a practitioner, she has worked with a diverse range of individuals including high-level youth and junior triathletes, AG triathletes, para-triathletes, long and ultra-distance runners, and cyclists. Her research is focused on optimising health and performance in endurance athletes and the general population.

References

1. Achten, J and Jeukendrup, A.E. Relation between plasma lactate concentration and fat oxidation rates over a wide range of exercise intensities. *International Journal of Sports Medicine*, 25 (1): 32-7. 2004.
2. Areta, JL, Burke, LM, Ross, ML, Camera, DM, West, DW, Broad, EM, Jeacocke, NA, Moore, DR, Stellingwerff, T, Phillips, SM, Hawley, JA, and Coffey, VG. Timing and distribution of protein ingestion during prolonged recovery from resistance exercise alters myofibrillar protein synthesis. *The Journal of Physiology* 591 (9): 2319-31. 2013.
3. Areta, JL and Hopkins, WG. Skeletal Muscle Glycogen Content at Rest and During Endurance Exercise in Humans: A Meta-Analysis. *Sports Medicine* (Auckland, N.Z.), 48 (9): 2091-2102. 2018.
4. Arkinstall, MJ, Bruce, CR, Clark, SA, Rickards, CA, Burke, LM, and Hawley, JA. Regulation of fuel metabolism by preexercise muscle glycogen content and exercise intensity. *Journal of Applied Physiology* (Bethesda, Md:1985), 97 (6): 2275-83. 2004.
5. Armstrong, LE, Casa, DJ, Millard-Stafford, M, Moran, DS, Pyne, SW, and Roberts, WO. Exertional heat illness during training and competition. *Medicine and Science in Sports and Exercise*, 39 (3): 556-572. 2007.
6. Baker, LB. Sweating Rate and Sweat Sodium Concentration in Athletes: A Review of Methodology and Intra/Interindividual Variability. *Sports Medicine*, 47 (Suppl 1): 111-128. 2017.
7. Baker, LB. Sweating rate and sweat sodium concentration in athletes: a review of methodology and intra/interindividual variability. *Sports Medicine*, 47 (1): 111-128. 2017.
8. Baker, LB and Jeukendrup, A.E. Optimal composition of fluid-replacement beverages. *Comprehensive Physiology*, 4 (2): 575-620. 2014.
9. Bartlett, JD, Hawley, JA, and Morton, J.P. Carbohydrate availability and exercise training adaptation: too much of a good thing? *European Journal of Sport Science*, 15 (1): 3-12. 2015.
10. Bartlett, JD, Louhelainen, J, Iqbal, Z, Cochran, AJ, Gibala, MJ, Gregson, W, Close, GL, Drust, B, and Morton, JP. Reduced carbohydrate availability enhances exercise-induced p53 signaling in human skeletal muscle: implications for mitochondrial biogenesis. *American journal of physiology. Regulatory, Integrative and Comparative Physiology*, 304 (6): R450-8. 2013.
11. Bassett, DR, Jr and Howley, ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine and Science in Sports and Exercise*, 32 (1): 70-84. 2000.
12. Bergstrom, J and Hultman, E. Muscle glycogen synthesis after exercise: an enhancing factor localized to the muscle cells in man. *Nature*, 210 (5033): 309-10. 1966.
13. Burke, LM, Hawley, JA, Jeukendrup, A, Morton, JP, Stellingwerff, T, and Maughan, RJ. Toward a common understanding of diet-exercise strategies to manipulate fuel availability for training and competition preparation in endurance sport. *International Journal of Sport Nutrition and Exercise Metabolism*, 28 (5): 451-463. 2018.
14. Burke, LM, Hawley, JA, Wong, SH, and Jeukendrup, AE. Carbohydrates for training and competition. *Journal of sports sciences*, 29 Suppl 1: S17-27. 2011.
15. Burke, LM, van Loon, LJC, and Hawley, JA. Postexercise muscle glycogen resynthesis in humans. *Journal of Applied Physiology* (1985), 122 (5): 1055-1067. 2017.
16. Casazza, GA, Tovar, AP, Richardson, CE, Cortez, AN, and Davis, BA. Energy Availability, Macronutrient Intake, and Nutritional Supplementation for Improving Exercise Performance in Endurance Athletes. *Current Sports Medicine Reports*, 17 (6): 215-223. 2018.
17. Cheuvront, SN and Kenefick, R.W. Dehydration: physiology, assessment, and performance effects.

Comprehensive Physiology, 4 (1): 257-285. 2011.

18. Costa, RJS, Snipe, RMJ, Kitic, CM, and Gibson, PR. Systematic review: exercise-induced gastrointestinal syndrome-implications for health and intestinal disease. *Alimentary Pharmacology & Therapeutics*, 46 (3): 246-265. 2017.
19. Coyle, EF, Coggan, AR, Hopper, MK, and Walters, TJ. Determinants of endurance in well-trained cyclists. *Journal of Applied Physiology* (1985), 64 (6): 2622-30. 1988.
20. Cuddy, JS, Slivka, DR, Hailes, WS, Dumke, CL, and Ruby, BC. Metabolic profile of the Ironman World Championships: a case study. *International Journal of Sports Physiology and Performance*, 5 (4): 570-6. 2010.
21. Da Boit, M, Hunter, AM, and Gray, SR. Fit with good fat? The role of n-3 polyunsaturated fatty acids on exercise performance. *Metabolism*, 66: 45-54. 2017.
22. de Oliveira, EP, Burini, RC, and Jeukendrup, A. Gastrointestinal complaints during exercise: prevalence, etiology, and nutritional recommendations. *Sports Medicine*, 44 Suppl 1: S79-85. 2014.
23. Doering, TM, Reaburn, PR, Phillips, SM, and Jenkins, DG. Postexercise Dietary Protein Strategies to Maximize Skeletal Muscle Repair and Remodeling in Masters Endurance Athletes: A Review. *International Journal of Sport Nutrition and Exercise Metabolism*, 26 (2): 168-78. 2016.
24. Farrokhyar, F, Sivakumar, G, Savage, K, Koziarz, A, Jamshidi, S, Ayeni, O, Peterson, D, and Bhandari, M. Effects of Vitamin D Supplementation on Serum 25-Hydroxyvitamin D Concentrations and Physical Performance in Athletes: A Systematic Review and Meta-analysis of Randomized Controlled Trials. *Sports Medicine*, 47 (11): 2323-2339. 2017.
25. Frandsen, J, Vest, SD, Larsen, S, Dela, F, and Helge, JW. Maximal Fat Oxidation is Related to Performance in an Ironman Triathlon. *International Journal of Sports Medicine*, 38 (13): 975-982. 2017.
26. Gonzalez, JT, Fuchs, CJ, Betts, JA, and van Loon, LJ. Liver glycogen metabolism during and after prolonged endurance-type exercise. *American Journal of Physiology. Endocrinology and Metabolism*, 311 (3): E543-53. 2016.
27. Guy, JH and Vincent, GE. Nutrition and Supplementation Considerations to Limit Endotoxemia When Exercising in the Heat. *Sports* (Basel, Switzerland), 6 (1). 2018.
28. Hawley, JA and Morton, JP. Ramping up the signal: promoting endurance training adaptation in skeletal muscle by nutritional manipulation. *Clinical and Experimental Pharmacology & Physiology*, 41 (8): 608-13. 2014.
29. Hearris, MA, Hammond, KM, Fell, JM, and Morton, JP. Regulation of Muscle Glycogen Metabolism during Exercise: Implications for Endurance Performance and Training Adaptations. Nutrients, 10 (3). 2018.
30. Hearris, MA, Hammond, KM, Seaborne, RA, Stocks, B, Shepherd, SO, Philp, A, Sharples, AP, Morton, JP, and Louis, JB. Graded reductions in preexercise muscle glycogen impair exercise capacity but do not augment skeletal muscle cell signaling: implications for CHO periodization. *Journal of Applied Physiology* (1985), 126 (6): 1587-1597. 2019.
31. Hoffman, MD, Bross III, TL, and Hamilton, RT. Are we being drowned by overhydration advice on the Internet? *The Physician and Sportsmedicine*, 44 (4): 343-348. 2016.
32. Hoffman, MD and Myers, TM. Case study: symptomatic exercise-associated hyponatremia in an endurance runner despite sodium supplementation. *International Journal of Sport Nutrition and Exercise Metabolism*, 25 (6): 603-606. 2015.
33. Hoffman, MD, Stellingwerff, T, and Costa, RJ. Considerations for ultra-endurance activities: Part 2–hydration. *Research in Sports Medicine*, 27 (2): 182-194. 2019.
34. Hoffman, MD and Stuempfle, KJ. Hydration strategies, weight change and performance in a 161 km ultramarathon. *Research in Sports Medicine*, 22 (3): 213-225. 2014.
35. Holmes, N, Bates, G, Zhao, Y, Sherriff, J, and Miller, V. The Effect of Exercise Intensity on Sweat Rate and Sweat Sodium and Potassium Losses in Trained Endurance Athletes. *Annals of Sports Medicine and Research*, 3 (2): 1-4. 2016.
36. Hulston, CJ, Venables, MC, Mann, CH, Martin, C, Philp, A, Baar, K, and Jeukendrup, AE. Training with low muscle glycogen enhances fat metabolism in well-trained cyclists. *Medicine and Science in Sports and Exercise*, 42 (11): 2046-55. 2010.
37. Impey, SG, Hammond, KM, Shepherd, SO, Sharples, AP, Stewart, C, Limb, M, Smith, K, Philp, A, Jeromson, S, Hamilton, DL, Close, GL, and Morton, JP. Fuel for the work required: a practical approach to amalgamating train-low paradigms for endurance athletes. *Physiological Reports*, 4 (10). 2016.
38. Impey, SG, Hearris, MA, Hammond, KM, Bartlett, JD, Louis, J, Close, GL, and Morton, JP. Fuel for the work required: a theoretical framework for carbohydrate periodization and the glycogen threshold hypothesis. *Sports Medicine*, 48 (5): 1031-1048. 2018.
39. Jager, R, Kerksick, CM, Campbell, BI, Cribb, PJ, Wells, SD, Skwiat, TM, Purpura, M, Ziegenfuss, TN, Ferrando, AA, Arent, SM, Smith-Ryan, AE, Stout, JR, Arciero, PJ, Ormsbee, MJ, Taylor, LW, Wilborn, CD, Kalman, DS, Kreider, RB, Willoughby, DS, Hoffman, JR, Krzykowski, JL, and Antonio, J. International Society of Sports Nutrition Position Stand: protein and exercise. *Journal of the International Society of Sports Nutrition*, 14: 20. 2017.
40. Jentjens, RL, Wagenmakers, AJ, and Jeukendrup, AE. Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. *Journal of Applied Physiology* (1985), 92 (4): 1562-72. 2002.
41. Jeukendrup, AE. Nutrition for endurance sports: marathon, triathlon, and road cycling. *Journal of Sports Sciences*, 29 Suppl 1: S91-9. 2011.
42. Jeukendrup, AE. Periodized Nutrition for Athletes. *Sports Medicine* (Auckland, N.Z.), 47 (Suppl 1): 51-63. 2017.
43. Jeukendrup, AE. Training the Gut for Athletes. *Sports Medicine* (Auckland, N.Z.), 47 (Suppl 1): 101-110. 2017.
44. Jeukendrup, AE and Killer, SC. The myths surrounding pre-exercise carbohydrate feeding. *Annals of Nutrition and Metabolism*, 57 Suppl 2: 18-25. 2010.
45. Jeukendrup, AE, Vet-Joop, K, Sturk, A, Stegen, JH, Senden, J, Saris, WH, and Wagenmakers, AJ. Relationship between gastro-intestinal complaints and endotoxaemia, cytokine release and the acute-phase reaction during and after a long-distance triathlon in highly trained men. *Clinical Science* (London). 98 (1): 47-55. 2000.
46. Jeukendrup, AE and Wallis, GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. *International Journal of Sports Medicine*, 26 Suppl 1: S28-37. 2005.
47. Kimber, NE, Ross, JJ, Mason, SL, and Speedy, DB. Energy balance during an ironman triathlon in male and female triathletes. *International Journal of Sport Nutrition and Exercise Metabolism*, 12 (1): 47-62. 2002.
48. Knechtle, B, Zingg, MA, Rosemann, T, Stiefel, M, and Rust, CA. What predicts performance in ultra-triathlon races? - a comparison between Ironman distance triathlon and ultra-triathlon. *Open Access Journal of Sports Medicine*, 6: 149-59. 2015.
49. Kopetschny, H, Rowlands, D, Popovich, D, and Thomson, J. Long-Distance Triathletes' Intentions to Manipulate Energy and Macronutrient Intake Over a Training Macrocycle. *International Journal of Sport Nutrition and Exercise Metabolism*, 28 (5): 515-521. 2018.
50. Krogh, A and Lindhard, J. The Relative Value of Fat and Carbohydrate as Sources of Muscular Energy: With Appendices on the Correlation between Standard Metabolism and the Respiratory Quotient during Rest and Work. *The Biochemical Journal*, 14 (3-4): 290-363. 1920.
51. Laursen, PB and Rhodes, EC. Factors affecting performance in an ultraendurance triathlon. *Sports Medicine*, 31 (3): 195-209. 2001.
52. Laursen, PB, Suriano, R, Quod, MJ, Lee, H,

Abbiss, CR, Nosaka, K, Martin, DT, and Bishop, D. Core temperature and hydration status during an Ironman triathlon. *British Journal of Sports Medicine*, 40 (4): 320-5; discussion 325. 2006.

53. Marquet, L, Brisswalter, J, Louis, J,Tiollier, E, Burke, LM, Hawley, JA, and Hausswirth, C. Enhanced Endurance Performance by Periodization of Carbohydrate Intake: "Sleep Low" Strategy. *Medicine and Science in Sports and Exercise*, 48 (4): 663-72. 2016.
54. Marquet, LA, Hausswirth, C, Molle, O, Hawley, JA, Burke, LM, Tiollier, E, and Brisswalter, J. Periodization of Carbohydrate Intake: Short-Term Effect on Performance. *Nutrients*, 8 (12). 2016.
55. Masson, G and Lamarche, B. Many non-elite multisport endurance athletes do not meet sports nutrition recommendations for carbohydrates. *Applied Physiology, Nutrition, and Metabolism*, 41 (7): 728-34. 2016.
56. Maughan, R, Shirreffs, S, and Watson, P. Exercise, heat, hydration and the brain. *Journal of the American College of Nutrition*, 26 (sup5): 604S-612S. 2007.
57. Maunder, E, Kilding, AE, and Plews, DJ. Substrate Metabolism During Ironman Triathlon: Different Horses on the Same Courses. *Sports Medicine*, 48 (10): 2219-2226. 2018.
58. Montain, SJ and Coyle, EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *Journal of Applied Physiology* (1985), 73 (4): 1340-50. 1992.
59. Morgan, R, Patterson, M, and Nimmo, M. Acute effects of dehydration on sweat composition in men during prolonged exercise in the heat. *Acta Physiologica Scandinavica*, 182 (1): 37-43. 2004.
60. Morton, JP, Croft, L, Bartlett, JD, Maclaren, DP, Reilly, T, Evans, L, McArdle, A, and Drust, B. Reduced carbohydrate availability does not modulate training-induced heat shock protein adaptations but does upregulate oxidative enzyme activity in human skeletal muscle. *Journal of Applied Physiology* (1985), 106 (5): 1513-21. 2009.
61. Noakes, TD. Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine and Science in Sports*, 10 (3): 123-45. 2000.
62. Nolte, HW, Hew-Butler, T, Noakes, TD, and Duvenage, CS. Exercise-associated hyponatremic encephalopathy and exertional heatstroke in a soldier: high rates of fluid intake during exercise caused rather than prevented a fatal outcome. *The Physician and Sports medicine*, 43 (1): 93-98. 2015.
63. Nordby, P, Rosenkilde, M, Ploug, T, Westh, K, Feigh, M, Nielsen, NB, Helge, JW, and Stallknecht, B. Independent effects of endurance training and weight loss on peak fat oxidation in moderately overweight men: a randomized controlled trial. *Journal of Applied Physiology* (1985), 118 (7): 803-10. 2015.
64. Pfeiffer, B, Stellingwerff, T, Hodgson, AB, Randell, R, Pottgen, K, Res, P, and Jeukendrup, AE. Nutritional intake and gastrointestinal problems during competitive endurance events. *Medicine and Science in Sports and Exercise*, 44 (2): 344-51. 2012.
65. Phillips, SM and Van Loon, LJ. Dietary protein for athletes: from requirements to optimum adaptation. 29 Suppl 1: S29-38. 2011.
66. Philp, A, Burke, LM, and Baar, K. Altering endogenous carbohydrate availability to support training adaptations. *Nestlé Nutrition Institute Workshop Series*, 69: 19-31; discussion 31-7. 2011.
67. Pilegaard, H, Osada, T, Andersen, LT, Helge, JW, Saltin, B, and Neufer, PD. Substrate availability and transcriptional regulation of metabolic genes in human skeletal muscle during recovery from exercise. *Metabolism*, 54 (8): 1048-55. 2005.
68. Pugh, JN, Kirk, B, Fearn, R, Morton, JP, and Close, GL. Prevalence, Severity and Potential Nutritional Causes of Gastrointestinal Symptoms during a Marathon in Recreational Runners. *Nutrients*, 10 (7). 2018.
69. Pyne, DB, West, NP, Cox, AJ, and Cripps, AW. Probiotics supplementation for athletes - clinical and physiological effects. *European Journal of Sport Science*, 15 (1): 63-72. 2015.
70. Robins, A. Nutritional recommendations for competing in the Ironman triathlon. *Current Sports Medicine Reports*, 6 (4): 241-8. 2007.
71. Romijn, JA, Coyle, EF, Sidossis, LS, Gastaldelli, A, Horowitz, JF, Endert, E, and Wolfe, R.R. Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *The American Journal of Physiology*, 265 (3 Pt 1): E380-91. 1993.
72. Rowlands, DS and Houltham, SD. Multiple-Transportable Carbohydrate Effect on Long-Distance Triathlon Performance. *Medicine and Science in Sports and Exercise*, 49 (8): 1734-1744. 2017.
73. Sareban, M, Zugel, D, Koehler, K, Hartveg, P, Zugel, M, Schumann, U, Steinacker, JM, and Treff, G. Carbohydrate Intake in Form of Gel Is Associated With Increased Gastrointestinal Distress but Not With Performance Differences Compared With Liquid Carbohydrate Ingestion During Simulated Long-Distance Triathlon. *International Journal of Sport Nutrition and Exercise Metabolism*, 26 (2): 114-22. 2016.
74. Saunders, A, Dugas, J, Tucker, R, Lambert, M, and Noakes, T. The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. *Acta Physiologica Scandinavica*, 183 (3): 241-255. 2005.
75. Sawka, MN, Burke, LM, Eichner, ER, Maughan, RJ, Montain, SJ, and Stachenfeld, NS. American College of Sports Medicine position stand. Exercise and fluid replacement. *Medicine & Science in Sports & Exercise*, 39 (2): 377-90. 2007.
76. Sharwood, K, Collins, M, Goedecke, J, Wilson, G, and Noakes, T. Weight changes, medical complications, and performance during an Ironman triathlon. *British Journal of Sports Medicine*, 38 (6): 718-724. 2004.
77. Shirreffs, SM and Sawka, MN. Fluid and electrolyte needs for training, competition, and recovery. *Journal of Sports Sciences*, 29 Suppl 1: S39-46. 2011.
78. Sousa, C, Aguiar, S, Olher, R, Sales, M, Nikolaidis, P, Rosemann, T, Knechtle, B, and Simões, H. Hydration status after an Ironman triathlon: A meta-analysis. *Journal of Human Kinetics*. 2019.
79. Spriet, LL. New insights into the interaction of carbohydrate and fat metabolism during exercise. *Sports Medicine* (Auckland, N.Z.). 44 Suppl 1: S87-96. 2014.
80. Taylor, C, Bartlett, JD, van de Graaf, CS, Louhelainen, J, Coyne, V, Iqbal, Z, Maclaren, DP, Gregson, W, Close, GL, and Morton, JP. Protein ingestion does not impair exercise-induced AMPK signalling when in a glycogen-depleted state: implications for train-low compete-high. *European Journal of Applied Physiology*, 113 (6): 1457-68. 2013.
81. Thomas, DT, Erdman, KA, and Burke, LM. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and Athletic Performance. *Journal of the Academy of Nutrition and Dietetics*, 116 (3): 501-528. 2016.
82. Valentino, TR, Stuempfle, KJ, Kern, M, and Hoffman, MD. The influence of hydration state on thermoregulation during a 161-km ultramarathon. *Research in Sports Medicine*, 24 (3): 197-206. 2016.
83. van Loon, LJ. Use of intramuscular triacylglycerol as a substrate source during exercise in humans. *Journal of Applied Physiology*, 97 (4): 1170-1187. 2004.
84. van Loon, LJ, Greenhaff, PL, Constantin-Teodosiu, D, Saris, WH, and Wagenmakers, AJ. The effects of increasing exercise intensity on muscle fuel utilisation in humans. *The Journal of Physiology*, 536 (Pt 1): 295-304. 2001.
85. Volek, JS, Noakes, T, and Phinney, SD. Rethinking fat as a fuel for endurance exercise. *European Journal of Sport Science*, 15 (1): 13-20. 2015.
86. Yeo, WK, Paton, CD, Garnham, AP, Burke, LM, Carey, AL, and Hawley, JA. Skeletal muscle adaptation and performance responses to once a day versus twice every second day endurance training regimens. *Journal of Applied Physiology* (1985), 105 (5): 1462-70. 2008.