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Auckland University of Technology
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Andrew Kilding
Auckland University of Technology
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Daniel J Plews
Auckland University of Technology
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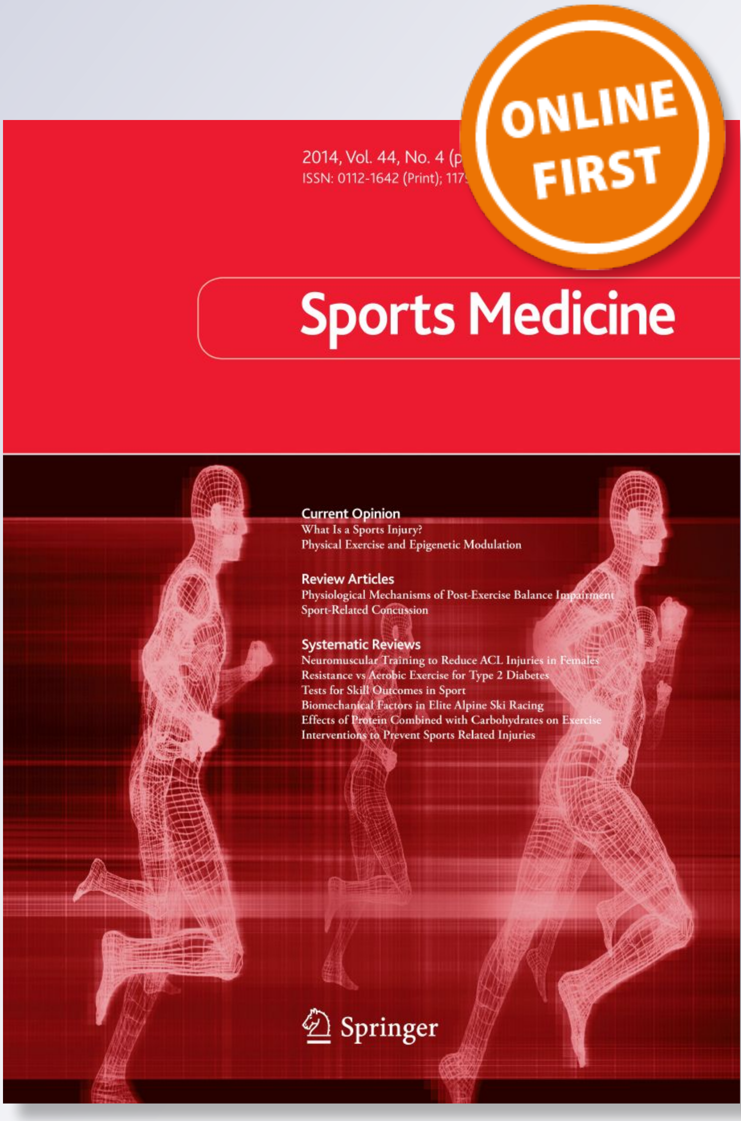

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CURRENT OPINION

Substrate Metabolism During Ironman Triathlon: Different Horses on the Same Courses

Ed Maunder[1] · Andrew E. Kilding[1] · Daniel J. Plews[1]

Abstract Ironman triathlons are ultra-endurance events of extreme duration. The performance level of those competing varies dramatically, with elite competitors finishing in ~ 8:00:00, and lower performing amateurs finishing in ~ 14–15:00:00. When applying appropriate values for swimming, cycling and running economies to these performance times, it is demonstrated that the absolute energy cost of these events is high, and the rate of energy expenditure increases in proportion with the athlete's competitive level. Given the finite human capacity for endogenous carbohydrate storage, minimising the endogenous carbohydrate cost associated with performing exercise at competitive intensities should be a goal of Ironman preparation. A range of strategies exist that may help to achieve this goal, including, but not limited to, adoption of a low-carbohydrate diet, exogenous carbohydrate supplementation and periodised training with low carbohydrate availability. Given the diverse metabolic stimuli evoked by Ironman triathlons at different performance levels, it is proposed that the performance level of the Ironman triathlete is considered when adopting metabolic strategies to minimise the endogenous carbohydrate cost associated with exercise at competitive intensities. Specifically, periodised training with low carbohydrate availability combined with exogenous carbohydrate supplementation during competition might be most appropriate for elite and top-amateur Ironman triathletes who elicit very high rates of energy expenditure. Conversely, the adoption of a low-carbohydrate or ketogenic diet might be appropriate for some lower performance amateurs (> 12 h), in whom associated high rates of fat oxidation may be almost completely sufficient to match the energy demands required.

Key Points

Ironman triathlons are ultra-endurance events where endogenous substrate availability is likely to be limiting, and are competed in by athletes across a vast range of performance levels.

Accordingly, the absolute energy cost of completing an Ironman triathlon is high, and application of published values for the energy cost of swimming, cycling and running demonstrates that the rate of energy expenditure varies considerably according to the performance standard of the individual athlete.

Therefore, the most appropriate preparatory strategy for Ironman triathletes may also vary according to the competitive level of the individual, given that the energy cost associated with performance also varies.

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✉ Ed Maunder
ed.maunder@aut.ac.nz

1 Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Rosedale, Auckland 0632, New Zealand

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1 Introduction

Ironman triathlons are ultra-endurance events consisting of a 3.9-km open water swim, 180-km cycle and 42.2-km run. They attract thousands of recreational to elite-level competitors each year. Elite professionals race throughout the year in an attempt to gain enough points to earn selection to the Ironman World Championships, which is held annually in Kona, Hawaii. Conversely, amateurs must place in a high-enough position within their age category in a single event race to qualify for the same race. Accordingly, the performance level range of those competing over the Ironman distance is vast. For example, in the 2017 European Ironman Championships in Frankfurt, finishing times varied from 7:41:42 to 14:56:07 within the 15-h cut-off time.

Exercise physiologists have comprehensively characterised traditional endurance events such as marathon running or prolonged time-trial cycling, with existing models suggesting endurance performance is physiologically determined by the athlete's maximal rate of oxygen consumption ($\dot{V}O_{2max}$), the lactate threshold or percentage of $\dot{V}O_{2max}$ that can be sustained and exercise economy [1–3]. Therefore, the goal of training for an endurance athlete is inevitably to improve these variables.

However, the physiology of *ultra*-endurance events is less well established. A further physiological consideration that might be of pertinence to ultra-endurance athletes, such as Ironman triathletes, is substrate metabolism and availability. During prolonged exercise, carbohydrate and fat are the primary substrates oxidised to fuel energy metabolism [4, 5]. The rate at which these substrates are oxidised is determined by numerous factors, with carbohydrate metabolism up-regulated by increasing exercise intensity [4] and environmental temperature [6–8]. Humans store the vast majority of endogenous carbohydrate as glycogen in skeletal muscle ($\sim$ 80%) and the liver ($\sim$ 10–15%) [9–13], and total endogenous carbohydrate storage typically amounts to $<$ 3000 kcal ($<$ 740 g) [14]. In contrast, human fat storage is vast, even in very lean individuals [14]. Indeed, it can be estimated that a 70-kg athlete with 10% body fat possesses $\sim$ 68,250 kcal (7000 g) of endogenous fat energy [15]. These disparities in substrate storage have implications for endurance athletes. Whilst, due to the greater rapidity and energy yield per litre of oxygen consumption (5.01 vs 4.85 kcal.L^{-1} O_2 for glycogen and fatty acid, respectively [15]), carbohydrate has been shown to be the most important metabolic substrate during exercise at moderate-to-high intensities [4, 5], skeletal muscle glycogen becomes depleted after exercise of sufficient length and intensity [9, 10, 16–19]. Mechanistically, intramyofibrillar glycogen depletion may specifically be associated with impaired excitation-contraction coupling and muscle fatigue [20]. In contrast, endogenous fat availability is effectively unlimited during endurance exercise. Therefore, Ironman triathletes should seek to minimise the endogenous carbohydrate cost associated with exercise at competitive intensities and delay fatigue associated with glycogen depletion.

2 Ironman Metabolism: Diverse Stimuli?

In order to explore the metabolic costs of Ironman triathlons at different performance levels, models were constructed for elite ($\sim$ 8 h), top-amateur ($\sim$ 9 h) and lower-amateur level ($\sim$ 13 h) finishers (Table 1). In order to do this, publically available data concerning Lionel Sanders' performance in the 2017 Kona Ironman were identified [21]. Sanders came second and completed the entire course in 8:04:07, with 0:53:41 to complete the 3.9-km swim, 4:14:19 to complete the 180.2-km cycle at a mean power of 313 W and 2:51:53 to complete the 42.2-km run. Best *estimates* of exercise economy, or energy cost, from existing literature were applied to these values to generate a rate of energy expenditure (kcal.min^{-1}) and absolute caloric cost (kcal) for each phase, and for the Ironman as a whole. Specifically, swim economy was estimated as $\sim$ 283.3 kcal.km^{-1} based on data in national-level Italian swimmers during a 2-km pool swim [22]; gross efficiency of cycling was estimated as 23%, the value reported in a recent case study of a Grand Tour-winning cyclist at a similar power output [23]; and running economy ($\sim$ 84.6 kcal.km^{-1}) was estimated as the average from a cohort of highly endurance-trained male runners ($\dot{V}O_{2max}$ = 75.5 $\pm$ 5.2 mL.kg^{-1}.min^{-1}) 2 km.h^{-1} below lactate turn-point, which equated to a mean speed of 15 km.h^{-1} (Sanders' mean running speed was 14.7 km.h^{-1}) [24].

For the top-amateur model, an author's 2015 Kona Ironman performance was used. DJP completed the course in 9:05:46, with 0:59:13 to complete the swim, 4:58:26 to complete the cycle at a mean power output of 225 W and 3:08:07 to complete the run, therefore finishing 46th overall (including professionals). This time would have placed sixth in the female competition, so might be used as a model of elite female performance. To generate a $\sim$ 13-h lower-amateur model, Sanders' times in each phase were increased by 63%, and mean power output during the cycle was estimated such that total mechanical work during the cycling phase was equal to Sanders'. Due to the paucity of data available for swimming economy, the same values as for Sanders were assumed. Gross cycling efficiency was estimated as 21.0% in the top-amateur model using data

Table 1 Theoretical model of the metabolic costs associated with performing an elite, top-amateur and lower-amateur Ironman triathlon

Phase	Intensity	Energy expenditure	Average FO ($g.min^{-1}$)	Fat oxidation (g)	CHO oxidation ($g.min^{-1}$)	CHO cost (g)
Elite						
Swim	$1.20\ m.s^{-1}$	$20.4\ kcal.min^{-1}$	Lower: 0.6	32	3.57	192
		1094 kcal	Upper: 1.2	64	2.13	115
Cycle	313 W	$19.5\ kcal.min^{-1}$	Lower: 0.6	153	3.35	853
		4959 kcal	Upper: 1.2	305	1.92	487
Run	$14.7\ km.h^{-1}$	$20.8\ kcal.min^{-1}$	Lower: 0.6	103	3.67	631
		3572 kcal	Upper: 1.2	206	2.23	383
Total	8:04:07	$20.1\ kcal.min^{-1}$	Lower: 0.6	288	3.49	1675
		9626 kcal	Upper: 1.2	576	2.05	985
Top-amateur						
Swim	$1.09\ m.s^{-1}$	$18.5\ kcal.min^{-1}$	Lower: 0.5	30	3.34	198
		1094 kcal	Upper: 1.1	65	1.91	113
Cycle	225 W	$15.4\ kcal.min^{-1}$	Lower: 0.5	149	2.57	768
		4580 kcal	Upper: 1.1	328	1.14	339
Run	$13.5\ km.h^{-1}$	$18.0\ kcal.min^{-1}$	Lower: 0.5	94	3.23	607
		3288 kcal	Upper: 1.1	207	1.79	337
Total	9:05:46	$16.6\ kcal.min^{-1}$	Lower: 0.5	273	2.88	1573
		9062 kcal	Upper: 1.1	600	1.44	788
Lower-amateur						
Swim	$0.74\ m.s^{-1}$	$12.5\ kcal.min^{-1}$	Lower: 0.3	26	2.35	206
		1094 kcal	Upper: 0.9	79	0.92	80
Cycle	192 W	$14.8\ kcal.min^{-1}$	Lower: 0.3	124	2.92	1209
		6133 kcal	Upper: 0.9	373	1.48	613
Run	$9.0\ km.h^{-1}$	$11.4\ kcal.min^{-1}$	Lower: 0.3	84	2.09	584
		3198 kcal	Upper: 0.9	252	0.65	182
Total	13:02:13	$13.3\ kcal.min^{-1}$	Lower: 0.3	235	2.56	1999
		10,425 kcal	Upper: 0.9	704	1.12	875

CHO carbohydrate, *FO* fat oxidation

from the 235-W stage of a 2016 step test performed by DJP, and 18.6% in the lower-amateur model, based on values reported in trained ($\dot{V}O_{2max} = 56.1 \pm 0.8\ mL.kg^{-1}.min^{-1}$) cyclists at 165 W [25]. Running economy for the top-amateur and lower-amateur models was estimated as the means of cohorts of well trained ($\dot{V}O_{2max} = 66.5 \pm 5.6\ mL.kg^{-1}.min^{-1}$, $\sim 80.3\ kcal.km^{-1}$ [26]) and trained ($\dot{V}O_{2max} = 55.5 \pm 0.8\ mL.kg^{-1}.min^{-1}$, $\sim 75.8\ kcal.km^{-1}$ [27]) males running at 85 and 75% of the speed at lactate threshold, which equated to 13.4 and $10.5\ km.h^{-1}$ on average, respectively. Body masses of 75 kg were assumed in the top-amateur and lower-amateur models.

Subsequently, wide lower and upper estimates of average fat oxidation rate were inputted to approximate the carbohydrate requirements of each phase and the overall Ironman, assuming 9.75 kcal.g fat^{-1}, 4.07 kcal.g $carbohydrate^{-1}$ and a negligible contribution from protein oxidation [15]. The *lower* estimated fat oxidation rate in the elite cohort was taken as the mean *maximum* fat oxidation value in a cohort of male triathletes [28], and this was reduced accordingly in the other cohorts. Furthermore, the authors' own laboratory measures confirm DJP's fat oxidation rate resides in the speculated top-amateur range during cycling when fat-adapted. The authors acknowledge and emphasise that this model is a postulated *estimate*, and full details regarding the models are available in the online spreadsheet (Electronic Supplementary Material Appendix S1). Readers are encouraged to adjust values as they see fit or in accordance with values measured in their own athletes.

Fatigue associated with depletion of endogenous carbohydrate is a consideration of particular importance to elite Ironman triathletes, given the high estimated absolute (9626 kcal over the entire race duration) and rate ($20.1\ kcal.min^{-1}$) of energy expenditure, which necessitates substantial carbohydrate utilisation (2.05–3.49 $g.min^{-1}$) even with concomitant high rates of fat oxidation (0.6–1.2 $g.min^{-1}$). Indeed, this estimated carbohydrate requirement (985–1675 g) exceeds the whole-body carbohydrate content [14], and is likely to be further exacerbated when one considers the hot environmental conditions in which Ironman triathlons are often performed (average temperature and relative humidity in Kona, Hawaii in October is ~ 30 °C, ~ 65% relative humidity, respectively) and the high-performance economy data used [22–24]. The estimated carbohydrate oxidation rates are noticeably reduced for top- (1.44–2.88 $g.min^{-1}$) and lower-amateurs (1.12–2.56 $g.min^{-1}$), underlining the diverse metabolic stimuli evoked by Ironman triathlons at different performance levels. These models provide theoretical insight into the potential substrate demands across performance levels and suggests that adjusting recommendations according to the competitive level of the athlete may be warranted. Notably, the estimated energy costs in this model are supported by similar mean measured values during an Ironman triathlon in eight males (10,036 ± 931 kcal) finishing in 10.9–13.0 h [29]. Importantly, this study reported significantly lower energy expenditure in five females (8570 ± 1014 kcal), an effect explained by differences in body mass. Accordingly, as the present models are based on male data, these values might be scaled down before application to female populations.

3 Ironman Goals: Metabolic Alterations to Last Longer and Go Faster

Ironman triathletes must therefore acknowledge these extreme metabolic costs in their preparation. Ironman triathletes should use their training to enhance the traditional physiological determinants of endurance performance, namely $\dot{V}O_{2max}$, lactate threshold, and exercise economy [1–3]. Given the multi-sport nature of triathlon events, these physiological characteristics must be trained specifically in swimming, cycling *and* running [30]. Furthermore, given the finite human capacity for carbohydrate energy storage [14] and the theoretical metabolic costs associated with Ironman performance (Table 1), a goal of pertinence for Ironman triathletes might also be to minimise the endogenous carbohydrate cost during exercise at competitive intensities [9, 10, 16–20]. The remainder of this article will therefore explore how Ironman triathletes might achieve the latter through nutrition and training, and how the optimal strategy might vary according to performance level.

4 Ironman Strategies: Striving to Preserve Endogenous Carbohydrate

4.1 Augmenting Fat Oxidation: Low-Carbohydrate Diets

A well documented, polarised debate exists regarding nutrition for endurance performance. Specifically, and simplistically, there are advocates of low-carbohydrate [31] and high-carbohydrate [32] dietary approaches. The rationale for low-carbohydrate, high-fat (LCHF, < 25% of energy from carbohydrate [33]), or ketogenic (< 20 g $carbohydrate.day^{-1}$ [33]) nutrition is the induction of adaptations promoting fat oxidation during prolonged exercise [34]. Indeed, robust increases in whole-body fat oxidation rates have been consistently observed in cross-sectional and interventional LCHF or ketogenic diet studies [35–38], which may be of interest to Ironman triathletes given the predicted extreme absolute energy cost associated with this event (Table 1). However, critics of this dietary approach have cited an apparent lack of beneficial effects on ecologically valid performance measures [33]. This may be attributable to possible carbohydrate restriction-induced down-regulation of enzymes involved in carbohydrate metabolism, and therefore reduced ability to harness carbohydrate substrate rapidly for brief periods of high-intensity work [39]. This remains a consideration for Ironman triathletes; Sanders' cycle phase included an ~ 12-min section averaging ~ 349 W during a pursuit [21], an increase in work rate inevitably resulting in increased carbohydrate oxidation [4, 5].

4.2 Augmenting Fat Oxidation: Training with Low Carbohydrate Availability

Exercise training *per se* has robust adaptive effects on fat metabolism, as evidenced by the greater utilisation of fat as a metabolic substrate at given absolute workloads in trained compared with untrained individuals [40], and in response to continuous [41] and interval-type [42] training regimens. A notable recent development is the low-carbohydrate training paradigm, in which carbohydrate intake is periodised [43]. This approach is based on the principle that skeletal muscle glycogen content acts as a signal for adaptation as well as a fuel store [44], and so performing exercise in a glycogen-depleted state, or after an overnight fast without provision of exogenous carbohydrate substrate, provides an additional metabolic stress driving cellular signalling and activation associated with exercise adaptation [45–47] (see Hawley and Morton [48]). Promising results in terms of whole-body fat oxidation rates during prolonged exercise have been reported in investigations examining this approach in previously endurance-trained athletes [49, 50]. However, concerns exist regarding whether the observed impairment in high-intensity power outputs during training with low-glycogen availability might lead to detraining effects [49, 50]. Accordingly, optimising 'train-low' practices is an important area of current and future research [51]. For instance, variations such as 'sleep-low' have recently been investigated. This involves high-intensity sessions performed in the evening with high-glycogen availability, before prolonged sessions with low-glycogen availability the following morning, and such variations appear promising in terms of metabolic and ecologically valid performance measures [52].

4.3 Provision of Additional Substrate: Exogenous Carbohydrate Supplementation

The more traditional high-carbohydrate approach seeks to load pre-exercise muscle and hepatic glycogen stores (10–12 g carbohydrate.kg^{-1}.day^{-1} for ~ 48 h prior to competition [32]), as well as provide optimised carbohydrate substrate exogenously during exercise. Indeed, a study of 53 finishers in the 2009 World Ironman Championship in Kona reported mean carbohydrate ingestion of 62 ± 26 g.h^{-1} [53]. The rationale for this approach is to maximise the athlete's absolute capacity for carbohydrate oxidation during the exercise bout, and delay fatigue associated with hypoglycaemia and/or depletion of stored glycogen [32]. *Ex*ogenous carbohydrate provision during exercise has been consistently shown to reduce *end*ogenous carbohydrate oxidation rates as these ingested carbohydrates are oxidised at rates up to ~ 1.8 g.min^{-1} [54–56]. However, advocates of LCHF have criticised the requirement for substantial exogenous carbohydrate provision given the possible accompanying gastrointestinal distress [31]. A study of Ironman triathletes reported > 30% prevalence of serious gastrointestinal issues, and correlated carbohydrate intake rate with self-reported nausea and flatulence, although inverse correlations between finishing time and carbohydrate intake rates were still observed ($r = -0.55$ to -0.45, $p < 0.001$) [53].

4.4 Provision of Additional Substrate: Exogenous Ketone Supplementation

An emerging area of research is exogenous ingestion of ketone esters and salts [57, 58]. The goal of a ketogenic diet is to reduce carbohydrate provision sufficiently to induce hepatic ketone synthesis and achieve ketosis [59], therefore providing skeletal muscle with ketone fuel sources and reduced requirement for carbohydrate oxidation. An alternative means of inducing ketosis, without having to make alterations to the chronic diet, is to ingest ketone esters to directly increase circulating concentrations [57]. Indeed, pre-exercise ingestion of the ketone ester D-β-hydroxybutyrate (D-βHB) has been shown to induce both ketosis and estimated D-βHB oxidation of up to ~ 0.5 g.min^{-1} [60], or ~ 2.35 kcal.min^{-1} given D-βHB oxidation yields 4.69 kcal.g^{-1} (~ 4.86 kcal.L^{-1} O_2) [61]. However, a study in professional cyclists observed a 2 ± 1% impairment in a 31-km cycling time-trial performance with pre-exercise ketone *di*ester ingestion, possibly attributable to gastrointestinal discomfort and increased perceived exertion [62]. Intriguingly, whilst it is possible the ketosis-inducing effect of exogenous ketone ingestion is at least partially blunted in the fed state [63], it is also possible that ketone *mono*ester-carbohydrate co-ingestion might act to spare muscle glycogen during prolonged exercise compared with carbohydrate ingestion alone [60]. This research is very much in its infancy, and requires substantial further investigation and clarification before recommendations regarding optimal practices can be made to Ironman triathletes.

4.5 Ironman Strategies: Summary

Accordingly, given the importance of minimising the endogenous carbohydrate cost at competitive workloads for Ironman triathletes, the approaches described above may be of particular interest for those preparing for competition. Of course, the retention of top-end power is still an area of concern, particularly for elite competitors who require the capacity for intermittent high power outputs during races [21]. The most appropriate strategy or strategies are therefore likely dependent on the performance level of the Ironman in question, given the diverse metabolic stimuli evoked during these events as described above (Table 1).

5 Ironman Recommendations: An Individual Approach Determined by Performance Level

In order to achieve the stated metabolic goal of Ironman preparation—delaying the depletion of endogenous carbohydrate at competitive workloads—an individualised approach that acknowledges the performance level of the Ironman triathlete in question is advocated, along with a personalised nutritional approach.

5.1 Elite and Top-Amateur Ironman Triathletes (~ 8–9 h)

In elite Ironman triathletes, a cross-over approach designed to increase capacity for fat oxidation through training, whilst maximising pre-competition endogenous carbohydrate storage and exogenous carbohydrate provision during competition, is recommended. This is justified by the high rates of energy expenditure estimated during *elite* male Ironman performance (~ 20.1 $kcal.min^{-1}$), and inevitable accompanying carbohydrate cost even with very high rates of whole-body fat oxidation (Table 1). It is suggested that even the highest rates of fat oxidation achievable through dramatic changes in diet will be insufficient to match the required energy demand alone. Therefore, at elite performance levels, training interventions could include planned sessions performed with low carbohydrate availability in order to drive adaptations to fat metabolism, possibly alongside specific training sessions with high rates of exogenous carbohydrate ingestion mirroring regimens to be used in competition in an effort to 'train the gut' to reduce gastrointestinal complaints if required [64, 65]. This approach is designed to maximally spare the rate of endogenous carbohydrate utilisation during the Ironman itself (Fig. 1). Periodised carbohydrate intakes during training might be used to retain the capacity for rapid carbohydrate utilisation and performance in high-intensity sessions, and exogenous carbohydrate nutrition during competition should be from multiple-transportable sources to maximise utilisation and reduce the likelihood of gastrointestinal complaints compared with single carbohydrates (~ 0.8:1 fructose–glucose at 1.5–1.8 $g.min^{-1}$) [66]. These recommendations are echoed for top-amateur male, and therefore elite female Ironman triathletes, who are still estimated to require energy expenditures (~ 16.6 $kcal.min^{-1}$) likely exceeding that which can be provided by fat metabolism alone, particularly at hot environmental temperatures.

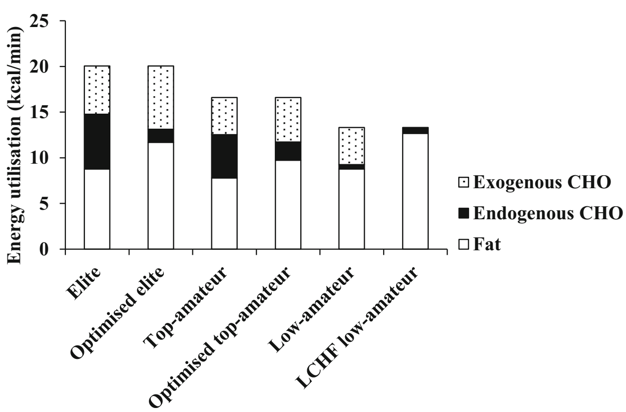

Fig. 1 Possible metabolic effects of performance-level-specific recommendations for elite, top-amateur and lower-amateur Ironman triathletes, displayed as illustrative, *estimated* contributions to the overall average rate of energy expenditure during an Ironman triathlon ($kcal.min^{-1}$). Exogenous carbohydrate utilisation is increased in the 'Optimised elite' and 'Optimised top-amateur' to demonstrate adherence to guidelines (~ 0.8:1 fructose–glucose at 1.5–1.8 $g.min^{-1}$) [66], fat utilisation is increased in the 'Optimised elite' and 'Optimised top-amateur' to demonstrate adaptations to the proposed training intervention, thus reducing endogenous carbohydrate utilisation. Fat utilisation is increased in the 'Optimised low-amateur' in accordance with proposed dietary changes, and exogenous carbohydrate utilisation is therefore obviated. *CHO* carbohydrate, *LCHF* low carbohydrate, high fat

5.2 Low-Performing Amateur Ironman Triathletes (~ 13 h)

In contrast, the lower estimated rate of energy expenditure (~ 13.3 $kcal.min^{-1}$) in low-performing amateur Ironman triathletes might allow a different strategy. It is plausible that adoption of a low-carbohydrate, or even ketogenic, dietary approach designed to maximise the capacity for fat oxidation during exercise might be sufficient to support the estimated rate of energy expenditure with minimal exogenous carbohydrate ingestion (Fig. 1). This approach may be favourable for those low-performing amateur Ironman triathletes exhibiting gastrointestinal discomfort with carbohydrate ingestion during competition, and who are focused primarily on simply completing the event. However, it should be acknowledged that the specific performance effects of adopting this dietary approach for Ironman triathlon are not known.

6 Conclusion and Practical Applications

Estimated rates of energy expenditure and carbohydrate utilisation are high in elite and top-amateur Ironman triathletes, even with high average rates of fat oxidation. These Ironman triathletes might therefore adopt exercise training and nutritional practices designed to minimise the endogenous carbohydrate cost associated with competitive workloads through a cross-over approach. Possible strategies to drive adaptations to fat metabolism have been mentioned above and, regardless of the specific strategy, involve specific training with low carbohydrate availability. Optimised *exogenous* carbohydrate provision during competition is recommended to further reduce the *endogenous* carbohydrate oxidation. However, the lower estimated rates of energy expenditure and carbohydrate utilisation during low amateur-level Ironman triathlons are worthy considerations when preparing these athletes for competition, where dietary fat adaptation might be sufficient to support energy expenditure. In summary, the metabolic stimulus evoked during an Ironman varies according to performance level, and this might be considered when preparing for and competing in an Ironman competition.

Compliance with Ethical Standards

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Conflict of interest Daniel J. Plews competes in Ironman triathlons and coaches elite Ironman triathletes. Ed Maunder and Andrew E. Kilding declare that they have no conflicts of interest relevant to the content of this article.

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