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ORIGINAL ARTICLE

BODY COMPOSITION, NUTRITION AND SUPPLEMENTATION

Effect of a low carbohydrate, high fat diet *versus* a high carbohydrate diet on exercise efficiency and economy in recreational male athletes

A. Mireille BAART *, Hennes SCHAMINEE, Marco MENSINK, Rieneke TERINK

Division of Human Nutrition and Health, University of Wageningen, Wageningen, the Netherlands

*Corresponding author: A. Mireille Baart, University of Wageningen, P.O. Box 17, 6700 AA Wageningen, the Netherlands. E-mail: mireille.baart@wur.nl

ABSTRACT

BACKGROUND: Exercise efficiency and economy are key determinants of endurance exercise performance. In this cross-over intervention trial, we investigated the effect of adherence to a low carbohydrate, high fat (LCHF) diet *versus* a high carbohydrate (HC) diet on gross efficiency (GE) and (OC) during exercise, both after 2 days and after 14 days of adherence.
METHODS: Fourteen recreational male athletes followed a two-week LCHF diet (<10 energy % carbohydrate) and a two-week HC diet (>50 energy % carbohydrate), in random order, with a wash-out period of three weeks in between. After 2 and 14 days on each diet, the athletes performed a 90-minutes submaximal exercise session on a bicycle ergometer. Indirect calorimetry measurements were done after 60 minutes of exercise to calculate GE and OC.
RESULTS: GE was significantly lower on the LCHF diet compared to the HC diet, after 2 days (17.6±1.9 *vs.* 18.8±1.2%, P=0.011, for the LCHF and HC diet respectively), not after 14 days. OC was significantly higher on the LCHF diet compared to the HC diet, after 2 days (1191±138 *vs.* 1087±72 mL O_2/kCal, P=0.003, for the LCHF and HC diet respectively), and showed a strong tendency to remain higher after 14 days, P=0.018.
CONCLUSIONS: Although LCHF diets are popular strategies to increase fat oxidation during exercise, adherence to a LCHF diet was associated with a lower exercise efficiency and economy compared to a HC diet.

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KEY WORDS: Diet, high-protein low-carbohydrate; Exercise; Athletic performance.

In sports, athletes and coaches, as well as scientists, are constantly searching for strategies to improve exercise performance. This includes recognition of the key determinants of endurance performance, including exercise efficiency and economy.[1, 2] Exercise efficiency is a measure of effective work, and various types and definitions exists, among which is gross efficiency (GE).[3] GE is defined as the percentage of energy expenditure that appears as work output.[4] Exercise economy, also referred to as oxygen cost (OC), is defined as the oxygen requirement to produce a certain exercise output, such as a movement speed or power output, and a high OC implies a low economy. A small improvement in efficiency and/or economy may already contribute to an improvement in endurance performance. For example, mathematical modelling has been used to predict that 1% increase in GE could result in a 63-second improvement in a 40 km cycling time trial.[5]

Several factors have been shown to influence exercise efficiency and/or economy, of which the most important factors are training status,[6-9] fatigue,[10] gender,[11] and technique.[12-14] However, dietary status and nutritional factors might also play a role. Among the currently popular interests in sports nutrition are adaptation to low carbohydrate, high fat (LCHF) diets,[15] including ketogenic versions,[16] and the periodization of CHO availability in so-called "train low, compete high" strategies.[17] Whereas the latter concept is undertaken to enhance cellular adaptation to the training program including an increase in mitochondrial biogenesis,[17] adaptation to a LCHF diet is principally undertaken to retool the muscle to increase its use of fat as an exercise substrate and reduce the dependency on the relatively limited muscle glycogen stores.[16, 18-20] However, improvement of endurance performance following a LCHF diet is generally not observed.[21, 22]

Interestingly, dietary macronutrient composition can have an effect on exercise efficiency and economy. However, studies that investigated the effect of dietary macronutrient composition on exercise efficiency and economy are scarce. In one study among cyclists, a higher GE was observed when adhering to a high carbohydrate (HC) diet compared to adhering to a diet that contained either a low or a moderate amount of carbohydrates.[23] In another study among runners, it was shown that a ketogenic diet impaired exercise efficiency at a higher intensity, as evidenced by oxygen uptake that could not be explained by shifts in the respiratory exchange ratio (RER), *i.e.* the ratio between carbon dioxide output (VCO_2) and oxygen uptake (VO_2), from pre- to post-dietary conditions, whereas exercise efficiency was maintained when exercising at a lower intensity.[24] In a series of studies among elite race walkers, adaptation to a LCHF diet increased fat oxidation but resulted in an increased OC, *i.e.* reduced economy, to walk at the speeds relevant to real life competitive events.[25-28] Finally, in a study among swimmers, no difference in swimming economy was observed between swimmers who consumed a LCHF diet or a high carbohydrate, low fat (HCLF) diet.[29]

Despite these studies, knowledge of the effect of dietary macronutrient composition on exercise efficiency and economy is limited. Moreover, although different studies on exercise efficiency or economy used different periods of dietary intervention, the studies that have been published assessed exercise efficiency or economy in general only after a single period of dietary intervention. In order to take into account the importance of adaptation to a specific diet with regard to changes in efficiency and economy, it is necessary to study the effect of different periods of dietary intervention within the same subject. Therefore, the aim of the present study was to investigate the effect of adherence to a LCHF diet versus a HC diet on exercise efficiency and economy, more specifically on GE and OC, both after 2 days and after 14 days of adherence.

TABLE I.—*Study population characteristics (N.=14).*

Characteristic	Mean±SD
Age (years)	33±8
Height (cm)	182±5
Weight (kg)	76.4±5.4
BMI (kg/m²)	23.1±1.4
Training (hours/week)	5.6±1.1
VO_{2max} (mL/kg/min)	57.3±5.8
Max heart rate (bpm)	187±9
W_{max} (W)	346±46

BMI: Body Max Index; VO_{2max}: maximal aerobic capacity; W_{max}: maximal power output.

Materials and methods

Participants

For this study, data from a previously conducted study, aimed to identify differences in exercise-induced stress and metabolic responses between adherence to a LCHF diet and adherence to a HC diet, was used. The study population and protocol have been extensively described elsewhere.[30] In brief, the study population consisted of 14 recreational male athletes, aged 22-44 years, who trained at least four hours per week in a variety of sports (cycling, running, swimming, triathlon, climbing, football, volleyball, strength training). This corresponds to Tier 2 (trained/developmental athletes) of the recentely proposed framework to classify training and performance of athletes.[31] The athletes had no chronic diseases or injuries and no dietary restrictions such as food intolerances or specific diets. Study population characteristics can be found in Table I.

The athletes participated in an intervention trial with a cross-over design, consisting of two times two weeks of dietary intervention with a wash-out period during which they followed their habitual diet in between. The dietary intervention involved following either a LCHF diet or a HC diet. After 2 and 14 days of each dietary intervention, the athletes performed a 90 minutes exercise session on a bicycle ergometer, with indirect calorimetry measurements after 60 minutes of exercise. We chose to perform measurements after 2 days to represent (metabolic) stress, while after 14 days an adaptive response in metabolism may be expected. After a wash-out period of three weeks, the athletes followed the other diet and the exercise protocols were repeated. A three weeks wash-out period was based on results from previous studies showing that metabolic adaptations to a LCHF diet already occurred within five days[32] and that substrate utilization had changed back to baseline levels within five to six days after following a HC diet.[28] Athletes were randomly assigned to start with either the LCHF diet or the HC diet. Athletes were instructed to keep their physical activity level and training regimen the same during both dietary intervention periods.

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and approved by the Medical Ethical Committee of Wageningen University (approval number: NL6540408118; ClinicalTrials.gov ID: NCT04019730). Written informed consent was obtained from all participants prior to participation.

LCHF and HC diets

Prior to the first intervention, dietary intake was assessed using a 3-day food record (two week days and one weekend day, randomly assigned) in order to gain insight in eating habits and to estimate energy needs for the development of personalized diet plans. These food records were analyzed for the total energy and macronutrient intake using Compl-eat™ software (Department of Human Nutrition and Health, Wageningen University).[33] Personalized diet plans were designed based on the participants estimated total energy needs. In total, six energy groups were considered: from 10 to 15 MJ with increments of 1 MJ.

The intervention diets were either a LCHF diet (<10 energy [En] % carbohydrates and ~75 En% fats) or a moderate HC diet (~50 En% carbohydrates and ~35 En% fats). Protein intake was higher in the LCHF diet compared to the HC diet (16±1 *vs.* 15±0 En%, for the LCHF and HC diet, respectively), although this was not intended. Total energy intake was equal in both diets for each individual athlete.

Each athlete individually received nutritional counselling, prior to the LCHF diet and prior to the HC diet. A detailed menu for two weeks and some standard products were provided. For the LCHF diet these products were: 48+ cheese (cheese with more fat per 100 g), olive oil, margarine, nuts, low-carb bread and beet muffins. For the HC diet these were: 30+ cheese (cheese with less fat per 100 gram), sunflower oil, margarine, nuts, muesli bars, fruit juices. The detailed menu consisted of a shopping list, prescribed recipes for breakfast, lunch, dinner and snacks of every day of the week and information about drinks (water, coffee and tea without sugar or milk were allowed) and herbs. Athletes were instructed to strictly follow their personalized diets. They had to weigh the food products that they consumed, and they were asked to record any deviations from the prescribed diet. Leftovers from provided foods were returned and weighed at the end of each dietary intervention period. Dietary intake was assessed at the end of each intervention period by adding or subtracting the written deviations from the prescribed diet and by subtracting the leftovers from provided foods. Deviations from the prescribed diet plans were very small. An overview of habitual dietary intake at baseline, and dietary intake during both intervention periods is presented in Table II.

TABLE II.—*Reported daily dietary intake.*

Nutrient	Habitual diet	LCHF diet	HC diet	P value
Energy (kCal)	2961±528	3104±297	3075±298	0.221
Carbohydrate (g)	318±72	64±6	373±38	<0.001*
Carbohydrate (En%)	43±5	8±0	49±0	<0.001*
Fat (g)	122±29	254±25	116±11	<0.001*
Fat (En%)	36±6	73±1	33±0	<0.001*
Protein (g)	116±22	124±12	112±11	<0.001*
Protein (En%)	16±3	16±1	15±0	<0.001*

Data are presented as mean±SD.
P values represent differences between the LCHF and the HC diet and were obtained with a paired *t*-test; *statistical significance (P<0.05).

Exercise protocol

Prior to the first intervention, a maximal exercise test on a bicycle ergometer (Lode Excalibur, Groningen, The Netherlands) was performed. Oxygen consumption was measured with indirect calorimetry (Oxycon Carefusion, Hoechberg, Germany), to assess maximal aerobic capacity (VO_{2max}) and maximal power output (W_{max}). In addition, body height (Seca 213 portable stadiometer, Hamburg, Germany) and weight (Seca 761 scale) were measured.

After 2 and 14 days of each dietary intervention, the athletes performed a 90-minute exercise session on a bicycle ergometer. Athletes arrived at the research facility after an overnight fast. At the research facility, they consumed a standardized breakfast corresponding to the macronutrient composition of their intervention diet and customized to their energy needs. For the LCHF breakfast, mean energy content was 588 kCal (74 En% fat, 17 En% protein, 6 En% carbohydrate), and for the HC breakfast 505 kCal (34 En% fat, 15 En% protein, 48 En% carbohydrate). One and a half hour after breakfast they started a 90-minute exercise session on the bicycle ergometer. The exercise session consisted of 10 minutes warming-up followed by 80 minutes at 60% of the athlete's individual W_{max}. The warming up consisted of 5 minutes at 100 Watt (W), followed by 5 minutes at a power in between 100 W and their individual 60% W_{max}. If an athlete was unable to maintain the workload at 60% W_{max}, the power was decreased to a level at which the athlete could keep on cycling until the end of the 90 minutes exercise session. Any adaptations in workload were carefully recorded. Heart rate was measured using a heart rate belt (Polar T31-coded, Oulu, Finland). After 60 minutes of exercise, gaseous exchange was measured (Oxycon Carefusion, Hoechberg, Germany) during a five-minute period to assess VO_2, VCO_2 and the RER. Mean values for VO_2, VCO_2 and the RER were calculated within this five-minute period, and these mean values were used for further calculations and analyses. Athletes were allowed to drink plain water during the test, but were not allowed to eat. Directly after the exercise session, athletes where asked to indicate the rate of perceived exertion (RPE) using a Borg Scale.[34]

Calculation of oxidation rates, and exercise efficiency and economy measures

In order to obtain insight in the degree of metabolic adaptation after 2 days and after 14 days, carbohydrate and fat oxidation rates were calculated according to the non-protein respiratory quotient,[35] as follows:

$$\text{carbohydrate oxidation rate (g/min)} = 4.585 * \dot{V}CO_2\ \text{(L/min)} - 3.226 * \dot{V}O_2\ \text{(L/min)}$$

$$\text{fat oxidation rate (g/min)} = 1.695 * \dot{V}O_2\ \text{(L/min)} - 1.701 * \dot{V}CO_2\ \text{(L/min)}$$

GE, defined as the percentage of energy expenditure that appears as work output,[4] was calculated as follows:

$$\text{GE (\%)} = \text{work output (kCal/min)} / \text{energy expenditure (kCal/min)} * 100.$$

The work output was the power (W) at which the athlete was cycling during the measurements after 60 minutes of exercise, using a conversion factor of 0.0002388 kCal for 1 J. Energy expenditure was calculated using the VO_2 and RER values that were obtained with indirect calorimetry measurements, according to the formula of Lusk.[36] First, a "caloric value" was calculated as follows: caloric value (kCal/mL O_2) = 3.815+1.232 * RER. Subsequently, energy expenditure was calculated as: Energy expenditure (kCal/min) = caloric value (kCal/mL O_2) * VO_2 (mL/min).

OC was defined as oxygen consumption per kCal when cycling at a given power (*i.e.* the power after 60 minutes of exercise) and was calculated as follows:

$$\text{OC (mL } O_2\text{/kCal)} = VO_2\ \text{(mL/min)} / \text{work output (kCal/min)}.$$

Statistical analysis

A two-way repeated measures Analysis of Variance (ANOVA) was performed to assess potential effects of diet, time or their interaction, on GE, OC and on other exercise characteristics. The level of significance was set at $P<0.05$. Next, differences in GE, OC and other exercise characteristics between diets or measurement days were evaluated using paired *t*-tests. To adjust for multiple comparisons, we applied a Bonferroni correction: we divided alpha by four, the number of tests we performed, resulting

TABLE III.—*Exercise characteristics and exercise efficiency and economy measures during the four exercise sessions, after 60 minutes of exercise.*[36]

	LCHF diet			HC diet			P value LCHF *vs.* HC after 2 days	P value LCHF *vs.* HC after 14 days
	After 2 days	After 14 days	P value after 14 days *vs.* after 2 days	After 2 days	After 14 days	P value after 14 days *vs.* after 2 days		
Power (W)†	170±36	186±26	0.019	201±32	200±30	0.808	<0.001*	0.008*
VO_2 (mL/kg/min)	2870±516	3034±415	0.035	3119±474	3097±400	0.776	0.010*	0.414
RER	0.81±0.02	0.81±0.03	0.751	0.90±0.04	0.91±0.02	0.432	<0.001*	<0.001*
Carbohydrate oxidation rate (g/min)	1.46±0.40	1.50±0.45	0.714	2.84±0.80	2.94±0.60	0.561	<0.001*	<0.001*
Fat oxidation rate (g/min)	0.89±0.18	0.95±0.22	0.140	0.50±0.20	0.45±0.13	0.338	<0.001*	<0.001*
Energy expenditure (kCal/min)‡	13.8±2.5	14.6±2.0	0.040	15.4±2.4	15.3±2.0	0.843	0.003*	0.086
Heart rate (bpm)	165±13	170±11	0.014	163±18	165±14	0.633	0.652	0.001*
RPE score	18.0±1.4	17.3±1.7	0.151	15.5±2.7	16.1±2.0	0.300	0.001*	0.053
GE (%)	17.6±1.9	18.2±1.2	0.089	18.8±1.2	18.7±1.3	0.897	0.011*	0.182
OC (mL O_2/kCal)	1191±138	1143±75	0.111	1087±72	1088±78	0.954	0.003*	0.018

Data are presented as mean±SD.
VO_2: oxygen uptake; RER: respiratory exchange ratio; RPE: rate of perceived exertion.
P values are obtained with a paired *t*-test; *statistical significance ($P<0.0125$); †conversion factor to calculate work (kCal/min) output from power (W): 0.01433; ‡energy expenditure was calculated using VO_2 and RER values, according to the formula of Lusk.[36]

in a level of significance of $P<0.0125$ for the paired *t*-tests. Statistical analyses were performed with SPSS software (Version 23, IBM, Armonk, NY, USA).

Results

Exercise characteristics

An overview of the exercise characteristics during the four exercise sessions is presented in Table III.[36] At multiple occasions the workload had to be reduced during the exercise session. Athletes had more problems to maintain the workload at 60% W_{max} when adhering to the LCHF diet: 12 athletes were not able to maintain this after 2 days on the diet, and 9 athletes were not able to maintain this after 14 days. On the HC diet this was the case for 4 athletes after 2 days and 5 athletes after 14 days. As a result, mean power, and consequently mean work output and energy expenditure, was not equal during the four exercise sessions (Table III).[36]

The two-way repeated measures ANOVA identified significant diet effects for power (F=24.0; P<0.001), VO_2 (F=4.9; P=0.045), RER (F=101.4; P<0.001), carbohydrate oxidation rate (F=72.1, P<0.001), fat oxidation rate (F=71.3, P<0.001), energy expenditure (F=9.8; P=0.008), and RPE (F=17.7; P=0.001). No significant time effects were observed. However, interaction effects between diet and time were observed for power (F=6.8; P=0.22), heart rate (F=5.3; P=0.038), VO_2 (F=6.4; P=0.026), and energy expenditure (F=5.3; P=0.038).

Paired *t*-tests showed that power was significantly lower on the LCHF diet compared to the HC diet, both after 2 days and after 14 days (170±36 vs 201±32 W, P<0.001, after 2 days, and 186±26 vs 200±30 W, P=0.008, after 14 days, for the LCHF and HC diet respectively). Regarding the duration of dietary adherence, power tended to be lower after 2 days than after 14 days when adhering to the LCHF diet. This tendency was not observed for the HC diet. VO_2 was lower on the LCHF diet compared to the HC diet, however this difference was only significant after 2 days (2870±516 *vs.* 3119±474 mL/min, P=0.10, for the LCHF and HC diet respectively). Regarding the duration of dietary adherence, VO_2 tended to be lower after 2 days than after 14 days when adhering to the LCHF diet, but not when adhering to the HC diet. The RER was significantly lower on the LCHF diet compared to the HC diet, both after 2 days and after 14 days (0.81±0.02 *vs.* 0.90±0.04, P<0.001, after 2 days, and 0.81±0.03 *vs.* 0.91±0.02, P<0.001, after 14 days, for the LCHF and HC diet respectively). The carbohydrate oxidation rate was lower on the LCHF diet compared to the HC diet, both after 2 days and after 14 days (1.46±0.40 *vs.* 2.84±0.80, P<0.001, after 2 days, and 1.50±0.45 *vs.* 2.94±0.60, P<0.001, after 14 days, for the LCHF and HC diet respectively). Correspondingly, the fat oxidation rate was higher on the LCHF diet compared to the HC diet, both after 2 days and after 14 days (0.89±0.18 *vs.* 0.50±0.20, P<0.001, after 2 days, and 0.95±0.22 *vs.* 0.45±0.13, P<0.001, after 14 days, for the LCHF and HC diet respectively). Energy expenditure was lower on the LCHF diet compared to the HC diet, however, this difference was only significant after 2 days (13.8±2.5 vs 15.4±2.4 kCal/min, P=0.003, for the LCHF and HC diet respectively). Regarding the duration of dietary adherence, energy expenditure tended to be lower after 2 days than after 14 days when adhering to the LCHF diet, but not when adhering to the HC diet. Heart rate was higher on the LCHF diet compared to the HC diet, however, this difference was only significant after 14 days (170±11 *vs.* 165±14 bpm, P=0.001, for the LCHF and HC diet respectively). Regarding the duration of dietary adherence, heart rate tended to be lower after 2 days than after 14 days when adhering to the LCHF diet, but not when adhering to the HC diet. Athletes rated their perceived exertion during exercise higher when on the LCHF diet compared to the HC diet, however, this difference was only significant after 2 days (18.0±1.4 *vs.* 15.5±2.7, P=0.001, for the LCHF and HC diet respectively).

Exercise efficiency and economy measures

Exercise efficiency and economy measures during the four exercise sessions are presented in Table III.[36] The two-way repeated measures ANOVA indicated significant effects of diet on GE (F=10.2; P=0.007), and OC (F=20.1; P=0.001). No significant effects of time or interaction effects between diet and time on GE and OC were observed.

Paired *t*-tests showed that GE was lower on the LCHF diet compared to the HC diet, however, this difference was only significant after 2 days (17.6±1.9 *vs.* 18.8±1.2%, P=0.011, for the LCHF and HC diet respectively), not after 14 days (18.2±1.2 *vs.*18.7±1.3%, P=0.182, for the LCHF and HC diet respectively). OC was significantly higher on the LCHF diet compared to the HC diet after 2 days (1191±138 *vs.* 1087±72 mL O_2/kCal, P=0.003, for the LCHF and HC diet respectively), and showed a strong tendency to be higher on the LCHF diet compared to the HC diet after 14 days (1143±75 *vs.* 1088±0.78 mL O_2/kCal, P=0.018, for the LCHF and HC diet respectively).

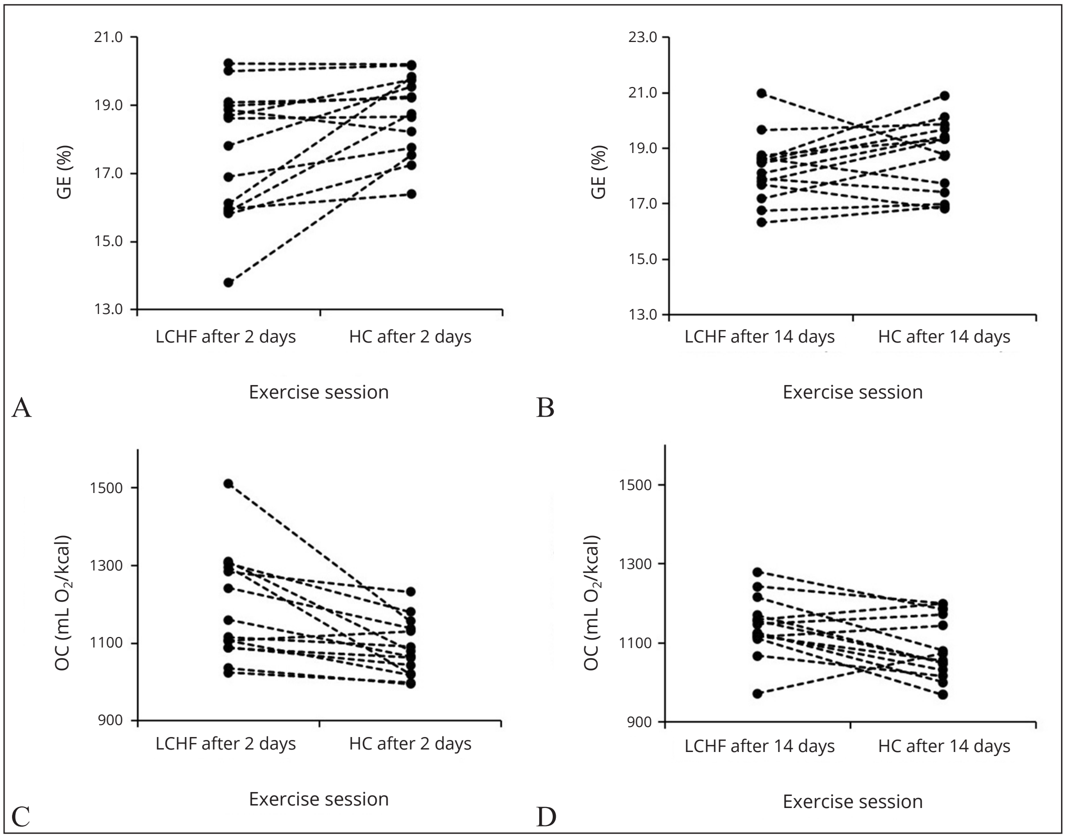

Figure 1.—GE and OC values for each individual athlete after 2 days (A and C) and after 14 days (B and D) of intervention, on either the LCHF or the HC diet.

Figure 1 presents GE and OC values for each individual athlete after 2 days (Figure 1A, C) and after 14 days (Figure 1B, D) of each dietary intervention. Individual differences in GE after 2 days of dietary intervention (LCHF diet *vs.* HC diet) ranged from -3.8% to +0.7%, with 12 out of 14 athletes having a lower GE on the LCHF diet. After 14 days, individual differences ranged from -2.3 to +2.2%, with 10 out of 14 athletes having a lower GE on the LCHF diet. For OC, individual differences (LCHF diet *vs.* HC diet) ranged from -25 to +353 O_2/kCal after 2 days, with 13 out of 14 athletes having a higher OC on the LCHF diet. After 14 days, individual differences ranged from and from -102 to +143 O_2/kCal, with 10 out of 14 athletes having a higher OC on the LCHF diet.

Discussion

The aim of this study was to investigate the effect of adherence to a LCHF diet versus a HC diet on exercise efficiency and economy, both after 2 days and after 14 days of adherence, in a group of recreational male athletes.

We observed a lower GE and a higher OC, thus a lower efficiency and a lower economy, when adhering to the LCHF diet compared to the HC diet. These differences were only statistically significant after 2 days on the diet, although there was a strong tendency for OC to remain higher after 14 days on the diet. These results replicate earlier observations[23-28] and resemble physiological differences expected after adaptation to a LCHF diet.

Effect of dietary macronutrient composition

Exercise economy, also referred to as OC, is defined as the oxygen requirement to produce a certain exercise output, such as a movement speed or power output[3] and a high OC implies a low economy. Exercise economy can be characterized in different ways, *e.g.* as VO_2 (mL/min) or as $\%VO_{2max}$ for a given workload or speed using a step-wise protocol.[24-28] We chose to use the term OC and to express it anchored to the changing workload in our study (mL O_2/kcal), as the intended 60% W_{max} exercise intensity had to be reduced on several occasions. Not correcting for these changes in workload would have flawed our observations.

A series of recent studies investigated the effect of adaptation to a LCHF diet on exercise economy in endurance athletes.[25-28] Elite race walkers consumed either a HC diet, a diet periodized within or between days to alternate between high and low carbohydrate availability, or a LCHF diet, during three weeks of intensified training. After three weeks of training, several measurements were performed to assess exercise metabolism and exercise economy and performance. Results showed that adaptation to a LCHF diet increased fat oxidation but resulted in an increased OC, *i.e.* reduced economy, to walk at the speeds relevant to real life competitive events. Results of the first study in these series[25] were replicated in a subsequent study.[26, 27] This observation is in line with our observed higher OC on the LCHF diet compared to the HC diet. Indeed, fat and carbohydrate have a different oxygen requirement, and consequently a different economy, for energy production due to their distinct metabolic pathways.[37] Stoichiometry of oxidation of substrates tells us that the OC is higher when relying more on fat oxidation as energy source when on a LCHF diet compared to a HC diet where carbohydrates are the dominant fuel. The oxidation of carbohydrates leads to a greater ATP yield per unit of oxygen consumption, or, vice versa, to a lower oxygen consumption for the same amount of energy, despite the greater ATP production per unit of substrate from fat.[37] Thus, the effect of dietary carbohydrate content on OC that we observed can be explained by the differences that occur in oxidation of fat and carbohydrates when adhering to either a LCHF diet or a HC diet, as can be seen in the lower RER, lower carbohydrate oxidation rate, and higher fat oxidation rate on the LCHF diet.

However, results from another study are not in line with our observation nor with those in the studies among race walkers.[25-28] In that study, the effect of dietary macronutrient composition on swimming economy was investigated.[29] Swimmers consumed either a LCHF or a HCLF diet for three days, after which they swam in a flume at velocities associated with 50, 60, and 70% of their VO_2max. Subjects swam at each velocity for 5 minutes and each trial was separated by a brief rest period. No difference in swimming economy was observed between the diets at each of the intensities, notwithstanding the lower RER on the LCHF diet compared to the HCLF diet, which doesn't match with our observation. The lack of power to detect small but relevant changes in exercise economy could underlie this.

Exercise efficiency is a measure of effective work, and various types and definitions exists, among which is GE,[3] which was investigated in the current study. GE is the percentage of energy expenditure that appears as work output,[4] and considers any additional increases in oxygen consumption beyond those predicted by the economy of fuel choices. The effect of dietary macronutrient composition on exercise efficiency is only scarcely investigated. In a study on GE, cyclists performed a 2-hour steady-state exercise session on a bicycle, after three days adherence to either a LCHF diet, a HC diet, or a diet that contained a moderate amount of carbohydrates.[23] Results from that study indicated a higher GE when adhering to a HC diet compared to adhering to a diet that contained either a low or a moderate amount of carbohydrates. This is in line with our observation that GE was lower on the LCHF diet after 2 days of dietary intervention. In another study, runners performed a run-to-exhaustion trial after 31 days adherence to either a ketogenic diet or their habitual diet.[24] Exercise efficiency was investigated by estimating oxygen uptake that could not be explained by shifts in RER from pre- to post-dietary conditions. Results showed that, after adherence to a ketogenic diet, at intensities above 70% VO_2max, the shifts in RER could not fully explain the increase in oxygen uptake, indicating impaired exercise efficiency. However, at lower intensities, particularly below 60% VO_{2max}, the shifts in fuel choice could fully explain the increase in oxygen uptake, indicating that exercise efficiency was not impaired. In line with this, we observed a lower GE on the LCHF diet when exercising at 60% W_{max}, although the difference was not significant after 14 days of adaptation. Changes in efficiency are subtle, and measuring gaseous exchange to calculate exercise efficiency and economy relies on precision and reliability of the measurements, which could have made us unable to detect a difference.

A reduced exercise efficiency or economy after adequate adaptation to a LCHF diet, greater than can be accounted for by stoichiometry of fat and CHO oxidation, should be explained by other factors. A change in the microbiome, and changes in nitrate/nitric oxide pathway, are suggested to play a role,[26, 27, 38] as well as increased mitochondrial uncoupling due to higher fatty acid-activated transcription factor peroxisome proliferator-activated receptor alpha.[24] This should, however, be explored further. A factor as muscle fatigue could also play a role, which is known to decrease exercise efficiency.[10] The ability of skeletal muscles to exercise is seriously compromised when endogenous glycogen stores are reduced to low levels prior to exercise, even when there is an abundance of other fuel sources.[18] Also, administration of carbohydrates during exercise can delay the onset of muscle fatigue.[39] Thus, a negative relationship exists between carbohydrate availability and fatigue. So, fatigue could be a mediating factor that underlies the lower GE on the LCHF diet, most likely due to a lower carbohydrate availability and reduced glycogen stores on the LCHF diet. The observed higher RPE scores on the LCHF diet, as well as the observation that the workload had to be reduced on more occasions on the LCHF diet, support this suggestion.

Duration of dietary adherence

We observed no statistically significant difference in GE and OC between measurements after 2 days and after 14 days, neither on the LCHF or HC diet. However, on the LCHF diet, GE tended to improve and OC to decrease, over time. Correspondingly, differences in GE and OC between the two diets were larger after 2 days than after 14 days on the diets. An explanation for this observation is that a short-term, *i.e.* 2 days, adherence to a LCHF diet reduces exercise capacity by depleting liver and muscle glycogen stores, without yet a full compensatory increase (adaptation) in fat oxidation,[40, 41] whereas long-term adherence to a LCHF diet increases breakdown, transport and oxidation of fat in skeletal muscle.[42] Indeed, fat oxidation rates were higher after 14 days than after 2 days on the LCHF diet, although this difference was not significant. Various studies suggest that it takes about five days for the muscle to metabolically adapt to either ketogenic or non-ketogenic versions of a LCHF diet.[26, 27, 32] So, after 2 days the body is in an acute energy crisis, *i.e.* body glycogen stores are low and fat oxidative capacity is not at peak level yet, while after 14 days adaptation has occurred. This 'crisis' is also reflected in the lower exercise capacity, *e.g.* lower power, VO_2, energy expenditure and heart rate, after 2 days compared to after 14 days on the LCHF diet, while cortisol levels and RPE were higher.[30] No difference in the RER was observed after 2 days compared to after 14 days on the LCHF diet. However, on both days the RER was significantly lower compared to the HC diet. This observation, which of course parallels the higher fat oxidation rates on the LCHF diet compared to the HC diet, indicates that fat is already the main fuel after 2 days on the LCHF diet. The smaller differences in GE and OC between the diets after 14 days indicate that adaptation to the LCHF diet takes place over time, however after 14 days GE and OC were not yet at the same level as on the HC diet. Whether an even longer adaptation period would result in comparable exercise efficiency and economy on the LCHF and the HC diet is questionable, because no further increase in fat oxidation is expected after five days.[32] On the other hand, results from a study among ultra-endurance athletes habitually consuming either a LCHF diet or a HC diet for at least six months showed very high fat oxidation rates during exercise in athletes adhering to a LCHF diet, but remarkably also equal resting muscle glycogen levels compared to athletes consuming a HC diet,[20] although other researchers question the results of that study.[43]

Practical implications

Although LCHF diets are popular strategies to increase fat oxidation from endogenous fat stores during endurance exercise performance,[20] partially relieving an athlete's dependency on glycogen stores,[16] we observed an unfavorable effect of adherence to a LCHF diet on exercise efficiency and economy. We investigated GE and OC using a bicycle ergometer, however results of this study might also be applicable to other endurance sports, such as running, swimming, triathlon, and race walking.

Exercise efficiency and economy are key determinants of endurance performance,[1, 2] and a small improvement in efficiency and/or economy may already contribute to an improvement in endurance performance. Several factors are known to influence exercise efficiency and/or economy, such as training status,[6-9] fatigue,[10] gender,[11] and technique.[12, 13] This study shows that nutritional factors can also affect exercise efficiency and economy, and accordingly, endurance performance. Based on the results of this study we would not recommend adhering to a LCHF diet for the purpose of exercise efficiency and economy. Future studies could investigate potential favorable nutritional strategies aiming to improve exercise efficiency and economy, and hence endurance performance.

Strengths and limitations of the study

To our knowledge this is the first study that considered the duration of adherence to a specific diet with regard to changes in exercise efficiency and economy, by performing measurements both after 2 days and after 14 days of dietary intervention, investigating both acute metabolic stress of, as well as adaptation to, a LCHF diet. When optimizing a dietary strategy aimed at increasing exercise efficiency and economy, knowledge about the effect of the duration of dietary adherence is essential.

Like any study, this study has some limitations. Although we aimed to use a steady-state exercise protocol at 60% W_{max}, the workload had to be reduced during the exercise session at multiple occasions. It is known that altering the exercise intensity influences the efficiency,[4, 44] and this could have influenced our results. However, although the workload had to be reduced more often on the LCHF diet, the observed higher heart rate and RPE scores on the LCHF diet indicate that the perceived intensity or effort was not lower. A familiarization session before the first test session could have identified athletes who might have problems to maintain the desired workload, and could have prevented the need to reduce the workload during the test sessions. The omission of a familiarization session might also have induced some bias through a potential learning effect with some improvement in cycling technique and reduced stress occurring after the first test session, rather than before the first test session. However, the cross-over design of the study takes away some of this bias.

Measurements were performed only once during the exercise session, after 60 minutes of exercise. Other studies in which multiple measurements over time were performed during an exercise session, indicated an effect of time on exercise efficiency.[23, 45] It could be possible that differences over time in efficiency and economy were present in the current study as well, but because of the single measurement these potential differences have not been recorded.

Calculation of the efficiency and economy measures GE and OC rely on the quality of the measurements of OCs, via indirect calorimetry, and the protocol used. The coefficient of variation for measuring gaseous exchange is close to expected differences in oxygen consumption between fat and carbohydrate oxidation. Exercise experience of participants, in general and with the protocol, will add to this variability. Our population consisted of recreational male athletes, not elite athletes, as was the population in several other studies,[20, 25-28] although participants were experienced cyclists. The recreational level of our athletes was reflected in the relative low fat oxidation rates observed after adaptation (0.95 g/min) compared to values observed in elite athletes,[20, 25-28] due to lower absolute power output in our athletes.

Furthermore, it is worth noting that we compared the effects of a LCHF to a HC diet, but we did not compare the effects of these diets with a 'standard' diet, although for most of the athletes the HC diet was very close to their habitual intake. Finally, the study population comprised only men. Gender is known to influence exercise efficiency.[11] Future studies could investigate whether the effect of diet on exercise efficiency and economy is different for men and women.

Conclusions

Results from this study showed an unfavorable effect of adherence to a LCHF diet on GE and OC, compared to adherence to a HC diet. Adhering to a LCHF diet impaired GE and OC, especially after 2 days of dietary intervention. In addition, results indicated that some adaptation to a LCHF diet takes place over time, however, GE and OC were not yet at the same level as on the HC diet after 14 days of dietary adherence. Although LCHF diets are popular strategies in sports to increase fat oxidation, we would not recommend adhering to a LCHF diet in order to improve endurance performance by increasing exercise efficiency and economy.

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