Effects of a Low Carbohydrate Weight Loss Diet on Exercise Capacity and Tolerance in Obese Subjects

Grant D. Brinkworth[1], Manny Noakes[1], Peter M. Clifton[1] and Jonathan D. Buckley[2]

Dietary restriction and increased physical activity are recommended for obesity treatment. Very low carbohydrate diets are used to promote weight loss, but their effects on physical function and exercise tolerance in overweight and obese individuals are largely unknown. The aim of this study was to compare the effects of a very low carbohydrate, high fat (LC) diet with a conventional high carbohydrate, low fat (HC) diet on aerobic capacity, fuel utilization during submaximal exercise, perceived exercise effort (RPE) and muscle strength. Sixty subjects (age: 49.2 ± 1.2 years; BMI: 33.6 ± 0.5 kg/m^2) were randomly assigned to an energy restricted (~6–7 MJ, 30% deficit), planned isocaloric LC or HC for 8 weeks. At baseline and week 8, subjects performed incremental treadmill exercise to exhaustion and handgrip and isometric knee extensor strength were assessed. Weight loss was greater in LC compared with HC (8.4 ± 0.4% and 6.7 ± 0.5%, respectively; $P = 0.01$ time × diet). Peak oxygen uptake and heart rate were unchanged in both groups ($P > 0.17$). Fat oxidation increased during submaximal exercise in LC but not HC ($P < 0.001$ time × diet effect). On both diets, perception of effort during submaximal exercise and handgrip strength decreased ($P \leq 0.03$ for time), but knee extensor strength remained unchanged ($P > 0.25$). An LC weight loss diet shifted fuel utilization toward greater fat oxidation during exercise, but had no detrimental effect on maximal or submaximal markers of aerobic exercise performance or muscle strength compared with an HC diet. Further studies are required to determine the interaction of LC diets with regular exercise training and the long-term health effects.

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INTRODUCTION

The obesity epidemic has led to increased interest in very low-carbohydrate "ketogenic" (LC) diets, such as the "Atkins diet" that are high in protein and fat as individuals seek effective weight loss strategies (1). The multiple benefits of regular physical exercise for health and facilitating weight loss are well established (2,3), leading to common consensus that exercise is an important adjunct to diet for obesity treatment (4,5). However, concern surrounds the potential for LC diets to deplete muscle and liver glycogen stores (6,7), leading to symptomatic side-effects of tiredness, weakness, or fatigue (8,9). These effects may reduce muscle performance, increase muscle fatigue, and adversely affect physical function and exercise tolerance that may compromise an individual's capacity to adhere to an exercise regime and reducing the usefulness of LC diets as part of a comprehensive weight loss program. However, the effect of an energy reduced, LC diet on exercise capacity and physical performance in sedentary, obese individuals has been poorly studied.

Early studies showed that maximal aerobic capacity ($\dot{V}O_{2max}$) was not impaired in obese patients following very low energy (≤3.5 MJ/day), carbohydrate restricted, ketogenic diets of relatively short duration (between 4 and 6 weeks) (10–12). However, effects on the capacity to perform submaximal aerobic exercise to exhaustion are equivocal, with enhancements (11), impairments (10), or no effect (13,14) being reported. The discrepant findings may reflect differences in several important aspects of study design, including the type and intensity of aerobic exercise investigated and varying macronutrient contents of the dietary interventions. These previous studies (10–13) were also limited by small sample sizes, in some cases lacked an appropriate control group (11,12), the use of relatively short intervention periods, and very low energy intakes (≤3.5 MJ/day) whereas moderate dietary restriction (4.2–6.2 MJ/day) is recommended for weight management (4,5). Therefore, the data presently available do not allow for conclusive interpretation of the chronic effects of an LC dietary pattern on the ability to undertake concurrent exercise as part of a comprehensive weight loss program in sedentary obese individuals, indicating the need for further research to substantiate previous findings.

[1]Preventative Health Flagship, Commonwealth Scientific and Industrial Research Organisation–Human Nutrition, Adelaide, South Australia, Australia; [2]Australian Technology Network (ATN) Centre for Metabolic Fitness and Nutritional Physiology Research Centre, University of South Australia, Division of Health Sciences, Adelaide, South Australia, Australia. Correspondence: Grant D. Brinkworth (grant.brinkworth@csiro.au)

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In addition to aerobic fitness, muscle strength is important for maintaining physical function and is an independent predictor of all-cause mortality (3), but the effects of LC diets on muscle strength in obese subjects is poorly understood. The aim of this study was to compare the effects of a moderate energy restricted, LC diet with an isocaloric high carbohydrate, low fat (HC) diet on aerobic exercise capacity, muscle strength, and metabolic adaptations to exercise in a large group of sedentary, overweight, and obese subjects.

METHODS AND PROCEDURES

Subjects

Figure 1 shows the participant flow. Subjects in the current investigation were a subsample of a larger study (15). The enrolment criteria, randomization process, and study design of the primary study has been described previously (15). The study was approved by the Human Ethics Committees of the Commonwealth Scientific and Industrial Research Organisation and the University of South Australia. In the primary study, 122 overweight/obese men and women (BMI 26–43 kg/m^2) with abdominal obesity and at least one other metabolic risk factor (16), participated in an 8-week randomized parallel study, in which subjects consumed either an energy restricted, very low carbohydrate, high fat (LC) diet or an isocaloric conventional HC diet. Seventy-six subjects (LC = 38, HC = 38) from the primary study also agreed to participate in the current study, but six withdrew before study commencement (LC = 1, HC = 5) and another four did not complete baseline assessments (LC = 1, HC = 3). Of the 66 subjects who completed baseline assessments, six withdrew during the intervention. Two subjects in LC withdrew due to an inability to comply with the dietary protocol while another two in LC did not complete the physical performance tests at week 8 due to lower leg injuries unrelated to the study, and two subjects from the HC group were lost to follow-up. The data reported are for the 60 remaining subjects. At baseline, both groups were similarly matched for gender distribution (LC (9 men, 23 women), HC (13 men, 15 women)), age (LC 48.8 ± 1.6 years, HC 49.3 ± 1.7 years), weight, and BMI. The study was randomized, but due to the vast differences in the diet patterns being evaluated, the participants and the research dieticians delivering the diets could not be blinded. However, participants received identical levels of staff support and attention and the outcome assessors (data collectors and data analysts) were blinded to treatment assignment to minimize bias.

Study design

At baseline (week 0) and after the intervention (week 8) subjects attended the clinic on two separate occasions for assessment. One of the clinic visits occurred in the morning after an overnight fast, during which height and body mass were measured, a venous blood sample was drawn for the measurement of plasma ketone bodies and an incremental treadmill exercise test was performed. On a separate day, in the afternoon after a minimum 3-h fast, body composition was determined using dual-energy X-ray absorptiometry and peripheral muscle strength was assessed. Throughout the intervention, subjects attended the clinic at week 2, 4, and 6 after an overnight fast for a weight check and venous blood sample for the measurement of ketone bodies. Subjects were advised not to consume any alcohol or participate in vigorous physical activity 24 h before the clinic visits. Apart from the prescribed dietary

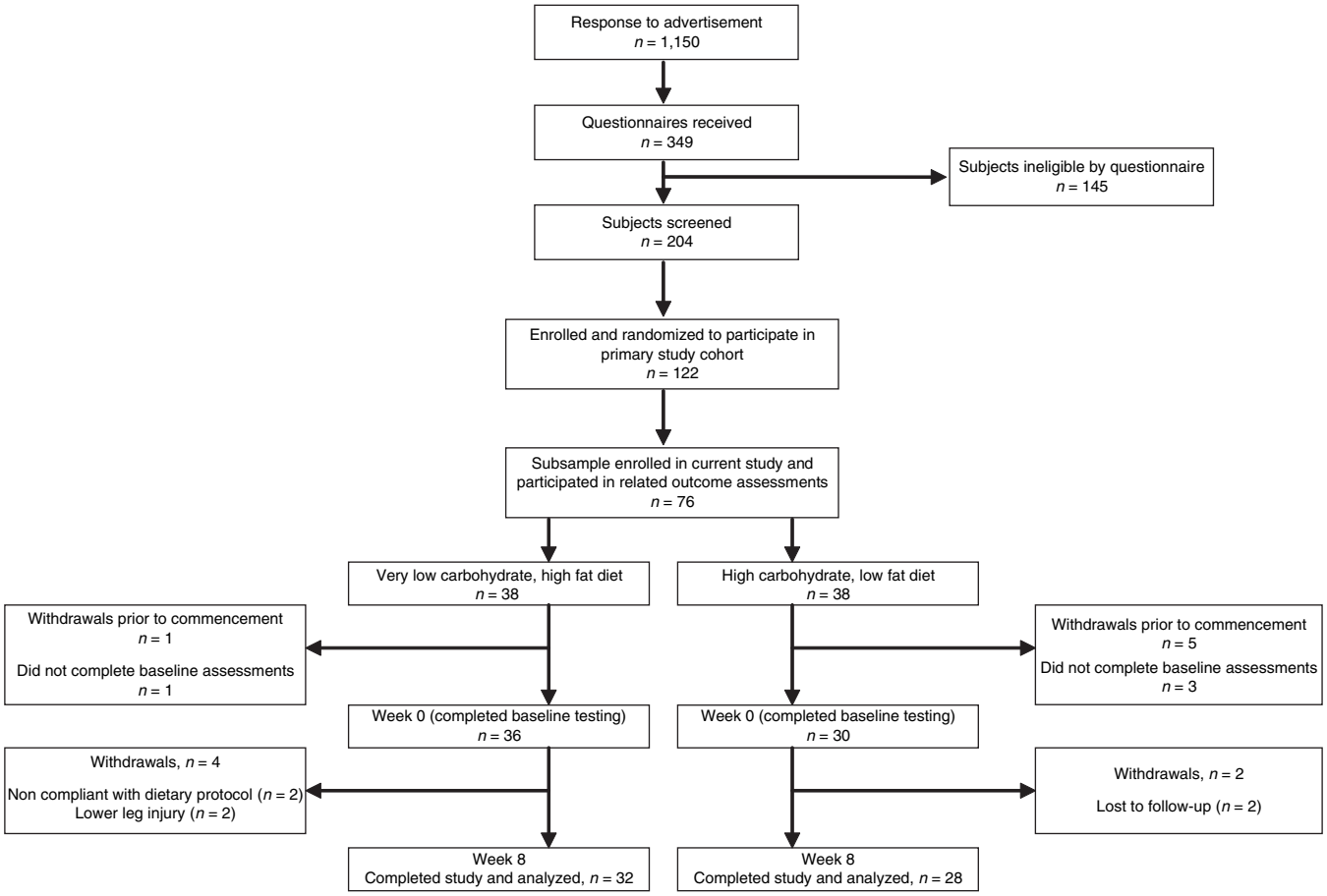

Figure 1 Flow of participants.

intervention, subjects were asked to maintain their usual lifestyle and physical activity habits throughout the study. Subjects completed a validated physical activity questionnaire (17), at weeks 0 and 8 to monitor physical activity levels.

Dietary intervention and assessment

The planned macronutrient profiles of the dietary interventions were: LC, 35% of energy as protein, 61% as fat, 4% as carbohydrate; HC, 24% of energy as protein, 30% as fat, and 46% as carbohydrate. The diets were designed to be isocaloric with a moderate energy restriction of ~30% of energy (providing ~6,000 kJ for women and ~7,000 kJ for men) for 8 weeks. Key foods representative of each diet's macronutrient profile were supplied at weeks 0, 2, 4, and 6 of the study to aid compliance. These foods were pre-weighed, generally uncooked and provided ~30% of total energy. The dietary plan was structured to include specific daily quantities of foods to ensure the correct macronutrient composition and energy intake, as described elsewhere (15). These foods and quantities consumed were recorded in daily food records. Detailed dietary advice, meal planning, and recipe information were provided at baseline and every 2 weeks by a qualified dietitian. Three consecutive days (one weekend and two weekdays) from the semi-quantitative food record of each 2-week period were analyzed, while the volunteer was present to ensure accuracy, using a computerized database (Foodworks Professional Edition, version 4 software, 1998; Xyris Software, Highgate Hill, Australia).

Height, body weight, and composition

Height (baseline only) was measured using a stadiometer (SECA, Hamburg, Germany) with subjects barefoot in the free-standing position. Body weight was measured using electronic digital scales (AMZ 14; Mercury, Tokyo, Japan) with subjects wearing light clothing and no footwear. Body composition (fat mass and nonbone lean mass) was assessed by dual-energy X-ray absorptiometry (Lunar Prodigy; General Electric, Madison, WI).

Submaximal exercise response and aerobic capacity

Peak oxygen uptake ($\dot{V}O_{2peak}$) was assessed during a maximal graded treadmill test to volitional exhaustion. The treadmill (Trackmaster TMX425CP; Full Vision, Newton, KS) speeds and grades for each stage were: stage 1, 4.8 km/h, 0%; stage 2, 4.8 km/h, 2.5%; stage 3, 4.8 km/h, 5%; stage 4, 4.8 km/h, 7.5%; stage 5, 4.8 km/h, 10%; stage 6, 4.8 km/h, 12.5%; stage 7, 4.8 km/h, 15.0%; stage 8, 4.8 km/h, 17.5%; stage 9, 4.8 km/h, 20.0%; stage 10, 4.8 km/h, 22.5%; stage 11, 5.5 km/h, 22.5%; stage 12, 6.7 km/h, 22.5%. Stage 1 was 5 min in duration and every stage thereafter was 3 min in duration. Subjects were verbally encouraged to exercise to volitional exhaustion. Measurements of oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and calculation of the respiratory exchange ratio (RER) were performed every 30 s using an automated indirect calorimetry system (TrueMax 2400; Parvomedics, Sandy, UT). The highest $\dot{V}O_2$ value achieved over a 30-s period was taken to represent $\dot{V}O_{2peak}$. Heart rate was recorded continuously throughout the incremental treadmill test and during the immediate recovery period as 5-s averages using a heart rate monitor and chest transmitter (S610i Polar Heart Rate Monitor; Polar Electro Oy, Kempele, Finland). A three-lead electrocardiogram was monitored continuously (CardioLife Tec-7100 Defibrillator; Nihon Kohden, Shinjuku-ku, Tokyo) and blood pressure was measured manually before exercise and at the end of each exercise stage for patient safety. Subjects rated their perceived exertion (RPE) according to the Borg scale (18), at the end of each exercise stage and at cessation of exercise. $\dot{V}O_{2peak}$ was deemed to have been reached, and the test data included in the analysis, if the subject achieved the primary criteria of a plateau in $\dot{V}O_2$ (increase of <150 ml/min) with increasing workload; or at least two of the three secondary criteria: (i) a peak RER (RER_{peak}) of ≥1.0, (ii) a peak heart rate (HR_{peak}) of ≥85% of age-predicted maximum (220 – age (years)), and (iii) rating of perceived exertion ≥17. Fat oxidation during the first stage of the treadmill test (i.e., during steady-state submaximal exercise) was calculated from gas exchange parameters during the final minute of exercise (19).

Muscular strength assessment

Grip strength of the dominant hand was measured using an adjustable, hydraulic handgrip dynamometer (JAMAR, Model 5030J1; Sammons Preston Roylan, Bolingbrook, IL) using the protocol of the American Society for Hand Therapists (20). Three maximal contractions were performed, with a 60-s rest between each. The highest value was used for analysis.

Peak isometric torque of the knee extensors of the dominant leg was assessed using an isokinetic dynamometer (Kin-Com 125AP; Chattecx, Chattanooga, TN), and taken to represent lower body muscular strength. Peak torque was taken to be the highest torque achieved from three maximal contractions with the knee at 90° of flexion, with a 2-min rest between efforts. Peak torque assessment was preceded by a warm-up consisting of 2-min cycling on an unloaded ergometer.

Biochemical analysis

Blood samples were collected into tubes containing EDTA/sodium fluoride. Plasma was separated by centrifugation at 2,000*g* at 4 °C for 10 min (GS-6R centrifuge; Beckman, Irvine, CA) and stored at −80 °C. Plasma ketone concentrations were analyzed in duplicate at the end of the study on a Hitachi auto analyzer using a RANBUT d-3-hydroxybutyrate kit (Randox Laboratories, Crumlin, UK).

Statistical analysis

Prior to hypothesis testing, a logarithmic transformation was performed for non-normally distributed variables (ketone bodies). Dietary data were compared using independent *t*-tests. Differences in baseline characteristics between groups were compared with univariate ANOVA for continuous variables and Pearson χ^2-test for categorical variables. The effect of the dietary intervention was assessed using repeated measures ANOVA with time as the within-subject factor and diet (LC vs. HC) and gender as between-subject factors. ANCOVA was also used where appropriate to adjust for differences in weight loss. Where there was a significant main effect, differences between means were determined *post hoc* with Bonferroni adjustment for multiple comparisons. Pearson's correlation analyses were used to determine relationships between variables. Statistical analyses were performed with SPSS 14.0 for WINDOWS (SPSS, Chicago, IL). Statistical significance was set at $P < 0.05$. All data are presented as means ± s.e.m.

RESULTS

Dietary analysis, physical activity, and compliance

The reported dietary intakes are consistent with the prescribed dietary treatments. There was no difference in total energy intake between the two diet groups (all subjects: LC 6,517.1 ± 101.6 kJ/day, HC 6,473.8 ± 152.6 kJ/day; $P = 0.81$, (men: 7,212.7 ± 165.5 kJ/day, HC 7,044.7 ± 218.6 kJ/day, women: LC 6,245.0 ± 66.0 kJ/day, HC 5,979.1 ± 103.0 kJ/day; $P = 0.72$ diet × gender)). Compared with subjects in the HC diet group, subjects in LC diet group had significantly lower carbohydrate (LC 5.1 ± 0.2%, HC 47.3 ± 0.7%) and higher fat (LC 58.8 ± 0.4%, HC 27.0 ± 0.7%) and protein (LC 35.1 ± 0.3%, HC 24.2 ± 0.4%) intakes ($P < 0.001$ for all nutrients).

Plasma ketone (β-hydroxybutyrate) concentration was similar in both groups at baseline (LC 0.07 ± 0.1 mmol/l, HC 0.06 ± 0.01 mmol/l; $P = 0.80$). By week 2, β-hydroxybutyrate concentrations had increased significantly more and was three times higher in the LC diet group compared to the HC diet group (LC 0.49 ± 0.06 mmol/l, HC 0.14 ± 0.03 mmol/l;

Table 1 Body weight and composition before and after 8 weeks of energy restriction with either a very low carbohydrate, high fat (LC) diet or high carbohydrate, low fat (HC) diet

	LC		HC	
	Week 0	Week 8	Week 0	Week 8
Body weight (kg)*,**	94.4 ± 2.6	86.3 ± 2.2	98.1 ± 2.3	91.4 ± 2.2
Men	103.1 ± 4.3	93.1 ± 3.4	105.6 ± 1.9	99.0 ± 3.2
Women	90.9 ± 2.9	83.5 ± 2.6	91.6 ± 3.2	84.9 ± 2.9
Fat mass (kg)*,**	40.2 ± 1.8	34.1 ± 1.7	39.8 ± 1.5	34.7 ± 1.5
Men	36.4 ± 2.8	28.2 ± 2.8	36.9 ± 1.9	32.4 ± 2.1
Women	41.8 ± 2.2	36.6 ± 1.9	42.3 ± 2.2	36.7 ± 2.2
Nonbone fat-free mass (kg)*	51.4 ± 1.8	49.2 ± 1.5	55.2 ± 2.1	53.6 ± 1.9
Men	63.5 ± 2.7	61.5 ± 1.8	65.4 ± 1.2	63.2 ± 1.3
Women	46.4 ± 1.1	44.2 ± 0.9	46.4 ± 1.4	45.3 ± 1.3
BMI (kg/m^2)**	33.7 ± 0.7	30.8 ± 0.6	33.7 ± 0.8	31.4 ± 0.8
Men	33.2 ± 1.3	29.9 ± 1.0	33.2 ± 1.0	31.1 ± 1.0
Women	34.0 ± 0.9	31.2 ± 0.8	34.1 ± 1.2	31.6 ± 1.1

Values are means ± s.e.m.
*P < 0.05, significant difference for baseline comparisons between men and women. **P < 0.05, significant time × diet × gender interaction for a greater reduction in LC compared to HC for men.

Table 2 Outcome parameters from the incremental exercise test before and after 8 weeks of energy restriction with either a very low carbohydrate, high fat (LC) diet or high carbohydrate, low fat (HC) diet

	LC		HC	
	Week 0	Week 8	Week 0	Week 8
Maximal exercise				
Time to exhaustion (min)*	18.7 ± 0.9	20.0 ± 0.9***	18.9 ± 0.7	20.4 ± 0.9***
Men	23.3 ± 1.9	24.8 ± 1.7	22.0 ± 0.8	23.9 ± 1.0
Women	17.0 ± 0.7	18.1 ± 0.7	16.3 ± 0.7	17.3 ± 0.8
$\dot{V}O_{2peak}$ (l/min)*	2.57 ± 0.12	2.44 ± 0.11***	2.71 ± 0.14	2.60 ± 0.14***
Men	3.44 ± 0.18	3.25 ± 0.14	3.34 ± 0.11	3.22 ± 0.14
Women	2.23 ± 0.07	2.12 ± 0.06	2.19 ± 0.10	2.07 ± 0.08
$\dot{V}O_{2peak}$ (ml·kg/min)*	27.6 ± 1.2	28.0 ± 1.1	27.7 ± 1.0	28.4 ± 1.2
Men	34.4 ± 2.2	33.5 ± 2.5	31.8 ± 1.0	32.8 ± 1.6
Women	25.0 ± 0.9	25.9 ± 0.9	24.2 ± 0.8	24.7 ± 0.9
RER_{peak}†	1.08 ± 0.01	1.03 ± 0.01***	1.09 ± 0.01	1.08 ± 0.01
HR_{peak} (beats/min)	171.2 ± 1.4	172.5 ± 2.4	166.5 ± 2.8	165.1 ± 2.6
RPE_{peak}	17.9 ± 0.2	18.5 ± 0.2	18.2 ± 0.3	18.3 ± 0.3
Submaximal exercise				
RER†	0.84 ± 0.01	0.77 ± 0.01***	0.82 ± 0.01	0.81 ± 0.01
Men	0.83 ± 0.03	0.75 ± 0.01	0.81 ± 0.01	0.80 ± 0.02
Women	0.84 ± 0.01	0.77 ± 0.01	0.84 ± 0.01	0.82 ± 0.01
Fat oxidation (g/min)*,†	0.33 ± 0.02	0.45 ± 0.03***	0.37 ± 0.02	0.35 ± 0.02
Men	0.38 ± 0.04	0.53 ± 0.06	0.44 ± 0.03	0.40 ± 0.03
Women	0.32 ± 0.02	0.42 ± 0.02	0.32 ± 0.02	0.31 ± 0.02
RPE[a]	10.1 ± 0.3	9.4 ± 0.3**	10.2 ± 0.3	9.9 ± 0.3**

Values are means ± s.e.m.
HR, heart rate; RER, respiratory exchange ratio; RPE, rating of perceived exertion; $\dot{V}O_2$, oxygen uptake.
[a]Score represent average of rating recorded at the end of 5 min and 8 min of exercise.
*$P \leq 0.001$, significant baseline differences between men and women. **P < 0.05, ***P < 0.001, significantly different from baseline within each group (time effect),
†$P \leq 0.005$ significant time × diet interaction for change in LC compared to HC.

Table 3 Maximal handgrip and isometric knee extensor strength before and after 8 weeks of energy restriction with either a very low carbohydrate, high fat (LC) diet or high carbohydrate, low fat (HC) diet

	LC		HC	
	Week 0	Week 8	Week 0	Week 8
Handgrip strength (kg)*	39.7 ± 2.2	35.2 ± 2.5**	42.3 ± 2.4	36.6 ± 2.4**
Men	55.4 ± 3.3	52.0 ± 3.5	52.3 ± 3.1	47.0 ± 3.1
Women	33.0 ± 0.9	28.0 ± 1.3	33.8 ± 1.5	27.8 ± 1.4
Isometric knee extensor strength (Nm)*	576.8 ± 43.4	602.5 ± 47.0	607.7 ± 47.3	631.5 ± 50.4
Men	844.9 ± 65.4	920.3 ± 68.6	805.2 ± 53.3	815.4 ± 69.2
Women	480.5 ± 34.3	484.8 ± 36.2	438.5 ± 34.1	473.9 ± 38.4

Values are means ± s.e.m.
*$P \leq 0.001$, significant difference for baseline comparisons between men and women. **$P < 0.001$ time effect, significantly different from baseline within each group.

$P < 0.001$ time × diet interaction) and remained significantly higher throughout the intervention indicating adherence to a very low carbohydrate intake in the LC group during the study.

At baseline there was no difference between diet groups in total physical activity score (LC 7.0 ± 1.1 arbitrary units, HC 7.1 ± 1.2 arbitrary units; $P = 0.74$) and this had not changed in either group by week 8 ($P = 0.90$).

Body weight and composition

There was a significant diet × time effect for body weight and BMI ($P = 0.02$, Table 1), due to greater weight loss in LC compared with HC (−8.4 ± 0.4% and −6.7 ± 0.5%, respectively). A significant gender effect was also evident ($P = 0.02$ time × diet × gender interaction), due to similar weight loss in both diet groups for women ($P = 0.39$), but greater weight loss in LC compared with HC for men ($P = 0.02$). Similarly, there was a diet × gender × time interaction for fat mass ($P = 0.01$) due to greater reductions in fat mass in men consuming the LC diet compared with HC diet ($P = 0.02$), but similar reductions for both diet groups in women ($P = 0.66$). Nonbone fat-free mass decreased during the intervention ($P < 0.001$), with no effect of diet or gender.

Exercise performance outcomes

Maximal exercise. At baseline, one subject in the HC diet group did not meet the criteria for a maximal treadmill exercise test and their data were excluded from analysis. By week 8, the time to exhaustion (TTE) during incremental treadmill exercise increased in both groups ($P < 0.001$), with no effect of diet or gender (Table 2). The increase in TTE correlated inversely with weight change ($r = -0.31$, $P = 0.02$), with the largest improvements occurring in subjects who experienced the greatest weight loss. Absolute $\dot{V}O_{2peak}$ reduced in both groups during the intervention ($P < 0.001$), but there was no change when expressed per kilogram of body weight (Table 2) and no interaction with diet or gender. There was a significant diet effect on RER_{peak} ($P = 0.005$ time × diet interaction), due to a decrease in subjects consuming LC ($P = 0.001$) and no change in HC ($P = 0.60$). HR_{peak} and RPE_{peak} at the end of the maximal exercise test did not change in either group.

Submaximal steady-state exercise. There was a significant effect of diet on the steady-state RER during the first submaximal workload of the graded treadmill test ($P < 0.001$, time × diet interaction) due to RER decreasing in LC ($P < 0.001$), but remaining unchanged in HC ($P = 0.24$), Table 2. Correspondingly, there was a significant time × diet interaction for fat oxidation during this same period of steady-state submaximal exercise ($P < 0.001$) with fat oxidation increasing in LC, but not changing in HC. There was no effect of gender on these responses. RPE during submaximal exercise was reduced in both groups at week 8 ($P = 0.03$ for time), with no difference in the response between the diets. At week 8, there was no correlation between plasma ketone concentration and RPE score during submaximal exercise ($r = -0.008$, $P = 0.95$).

Muscle strength. Maximal handgrip strength decreased during the intervention ($P < 0.001$), with no effect of diet or gender (Table 3). Maximal isometric knee extensor strength did not change in either group.

DISCUSSION

In the present study, no differences were found in the effects of isocaloric LC and HC weight loss diets on exercise function or perceptions of fatigue and exertion in a group of overweight and obese subjects. Diet composition altered fuel partitioning during exercise, with an increase in fat oxidation during submaximal aerobic exercise in the LC group.

Our finding of a small, but significantly greater weight loss in subjects who consumed the LC diet is consistent with several other short-term studies (21–23). Body composition assessment indicated that the greater weight loss was attributable to greater fat loss. Moreover, we observed evidence of a possible gender specific response for reductions in body weight and fat mass with consumption of LC in men, but not women. This magnitude of effect is similar to that observed in a previous smaller study (23), that also reported greater reductions in body and fat mass in men after an LC diet compared with an HC diet. The exact reason for this gender difference and the mechanisms regulating composition of weight loss and distribution of fat during LC diets cannot be determined from the present data, but could be mediated in part by hormonal

differences; sex-specific differences that could explain these differential responses between genders should be explored in further studies. Despite the weight loss differences between the groups in the present study, reported energy intakes did not reflect this. Alternatively, a meta-analysis of 94 studies concluded that "weight loss using LC diets was principally associated with decreased caloric intake and increased diet duration, not with reduced carbohydrate content" (24). However, this analysis was limited by the high heterogeneity between the studies that used a wide range of levels of carbohydrate intake to define "LC diets." In contrast, a more recent meta-regression that included more highly controlled dietary trials, showed that compared with higher carbohydrate intakes, LC diets had increased loss of body mass and body fat, even after control for energy intake (25). The origin of the difference in weight loss between LC and HC diets still remains controversial, with several hypotheses been proposed (23,25).

Although the issue of whether LC diets result in greater weight loss compared to HC diets is of interest, the primary purpose of this study was to evaluate the effects of LC diet on physical function and exercise tolerance. It has long been considered that aerobic exercise performance is highly dependent on carbohydrate availability and muscle glycogen content (26), with muscle becoming increasingly reliant on carbohydrate as a fuel source with increasing exercise intensity (27); however, we found no differences in maximal exercise parameters, including aerobic capacity or exercise tolerance between the diet groups. Previous very low energy weight loss studies have also shown no effect of an LC diet on $\dot{V}O_{2max}$ after 4–6 weeks in untrained obese subjects (10–12,14). These researchers also demonstrated that prolonged submaximal endurance capacity was sustained after 6 weeks of an LC diet, although a temporary reduction after 1 week occurred (11). Walberg *et al.* (14) found no difference in submaximal endurance performance between obese women consuming a very low energy LC or HC diet after 4 weeks. This suggests that metabolic adaptation to an LC diet may take longer than 1 week to manifest. In contrast, Bogardus *et al.* (10) demonstrated reductions in endurance exercise capacity in untrained obese women following 6 weeks of a hypocaloric LC diet compared to an HC diet. However, in that study subjects performed intermittent exercise at a high workload suggesting that LC diets may be detrimental to the ability to sustain high intensity exercise, where carbohydrate will be the predominant fuel source, but an increase in fat oxidation compensates for reduced carbohydrate availability during submaximal exercise. Other studies comparing LC and HC diets also show that a high carbohydrate intake can enhance physical function and work capacity in untrained individuals (26,28,29). However, these studies used relativity short dietary periods (≤7 days), providing further evidence that a period of longer than 1 week may be required to allow sufficient time for metabolic adaptation to carbohydrate restriction to be achieved.

In support of the notion of adaptation to carbohydrate restriction, White *et al.* (30) showed that RPE (a valid measure of perceived exercise effort) (31) during a submaximal exercise bout was directly related to blood ketones in overweight subjects consuming a hypocaloric LC or HC diet after 2 weeks, such that higher ketone levels were associated with an increased perception of effort. In contrast, we did not observe any difference in RPE score during exercise between the diet groups nor any relationship with blood ketone concentrations, suggesting that keto-adaptation over a more extended period may have occurred. Further studies should closely monitor the time course of metabolic changes in response to carbohydrate restriction, particularly during the early period of adaptation to an LC diet.

Endurance exercise performance (i.e., TTE during treadmill exercise) and the perception of effort during exercise did not differ between LC and HC. Since, RPE correlates with endurance performance (32), and we previously reported no differences in feelings of "fatigue," "vigor" or mood state following the consumption of either an LC or HC (15), our results suggests that an LC diet does not impact negatively on perceived effort or fatigability that could alter the desire or sustainability to exercise. In further support, we observed no change in physical activity levels reported by the subjects in either group. Conversely, a small pilot study suggested that, compared with an HC diet, consumption of an LC, ketogenic diet for 9–21 days was associated with a reduction in free living physical activity (9). However, this study was performed in normal weight subjects and the results may not apply to an overweight population during weight loss. Nevertheless, the effect of LC diets on the capacity to undertake tasks of daily living remains largely unexplored and warrants further investigation. Studies are also required to evaluate the perception and tolerance to undertaking a regular exercise program when combined with an LC diet.

Absolute aerobic capacity reduced with both diets during the study. This effect was most likely secondary to a decrease in weight and lean body mass, since $\dot{V}O_{2peak}$ normalized to body weight remained unchanged. This maintenance of aerobic fitness paralleled the data demonstrating that physical activity levels were maintained. Despite this, weight loss increased exercise tolerance as indicated by an increase in TTE. Others have also observed increases in exercise tolerance with weight loss in the absence of any observable change in $\dot{V}O_{2max}$ (14,33). Several factors could have contributed to this improved exercise performance, including increased familiarity with the treadmill (34), or increased motivation (35). Alternatively, since the weight loss itself correlated with the increase in exercise time, the increased TTE was most likely due to improved mechanical efficiency resulting from a reduced mechanical workload (due to a reduction in body weight) at any given treadmill speed and incline. An observed downward shift in $\dot{V}O_2$ at each workload after weight loss supports this proposition (data not shown).

RER is commonly used to estimate utilization of carbohydrate and fat during metabolism. Consistent with other studies (14,36,37), we observed a decline in RER during submaximal steady-state exercise with the LC diet, indicating greater utilization of fat and lower carbohydrate utilization. This supports the concept of adaptation and a shift in substrate utilization over time on an LC diet that might have enabled the maintenance

of exercise function and counteracted the reduction in carbohydrate and glycogen stores that occurs following LC diets (38,39). It has previously been shown that when obese subjects consumed an LC diet for 6 weeks and performed their usual activities (but not strenuous exercise), muscle glycogen content was reduced, albeit only moderately (by ~30%) (11). Although the present study was not designed to analyze the precise mechanisms driving the changes in fat oxidation following the LC diet, proposed metabolic and hormonal adaptations have been previously described (37,40). Additionally, it is likely that the shift from glucose to ketone body oxidation by the brain, as occurs during fasting (41), assists in preserving glycogen stores. This coupled with adaptations toward an ability to oxidize fat during exercise may have enabled the sustainability of aerobic exercise performance in the LC group in spite of markedly reduced dietary carbohydrate intake in the present study.

Muscle strength displayed similar responses in both groups, with reductions in handgrip strength, while knee extensor strength was maintained. Consistent with the latter finding, previous studies have shown maintenance of muscle strength following a short-term period of energy restriction in obese subjects (42,43). Conversely, the decline in grip strength is consistent with an earlier study (44), which reported decreases in grip strength after 12 weeks of energy restriction. Although a precise reason for the different effects on handgrip and knee extensor strength cannot be determined, it is possible that use of the lower body muscles during daily ambulation may have protected against loss of lean tissue (i.e., skeletal muscle) from the lower extremities and therefore assisted in maintaining lower body strength, whereas the reduction in handgrip strength may reflect an absence or lower involvement of the upper limbs in weight bearing activities, as previously suggested (45). Despite the fact that an LC diet was not shown to adversely affect muscular strength any more than an HC diet, muscle strength is important for performing normal daily living tasks, including physical exercise, that assist in maintaining an active lifestyle and protecting against disability (46). Hence, the addition of strength training to a weight loss diet may be an important adjunct for maintaining muscle strength (43).

In conclusion the current data suggest that in untrained, overweight individuals, the consumption of an LC weight loss diet for 8 weeks, does not adversely affect physical function or exercise tolerance compared with an HC diet. This suggests that, at least over the short-term, an LC weight loss diet is unlikely to limit an individual's ability or desire to participate in concomitant exercise which is unequivocally recognized as an important adjunct to diet for obesity treatment. Indeed, metabolic adaptations occur that elicit greater fat oxidation during submaximal exercise. However, further studies need to confirm whether LC diets alter the tolerance and sustainability for regular exercise and evaluate longer-term effects on physical function.

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DISCLOSURE

The authors declared no conflict of interest.

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