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Effects of a low-carbohydrate diet on weight loss and cardiometabolic profile in Chinese women: a randomised controlled feeding trial

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Abstract

Little is known about the potential adherence to and the effectiveness of a low-carbohydrate (LC) diet on weight loss and cardiometabolic risk factors in Chinese adults with a habitually high carbohydrate intake. In the present controlled feeding trial, fifty overweight or obese women (age 47·9 (SEM 0·9) years; BMI 26·7 (SEM 0·3) kg/m^2) were randomly assigned to a LC non-energy-restricted diet (initial carbohydrate intake 20 g/d, with a 10 g increase weekly) or an energy-restricted (ER) diet (carbohydrate intake 156–205 g/d, ER to 5021 or 6276 kJ/d, 35 % average energy reduction) for 12 weeks. Over the intervention period, the two diets had comparable compliance (96 %) and self-reported acceptability. At week 12, carbohydrate intake in the LC and ER groups contributed to 36·1 and 51·1 % of total energy, respectively ($P<0·001$). Although both diets showed similarly decreased mean body weight (LC −5·27 (95 % CI −6·08, −4·46) kg; ER −5·09 (95 % CI −5·50, −4·67) kg, $P=0·67$) and percentage of fat mass measured by dual-energy X-ray absorptiometry (LC −1·19 (95 % CI −1·88, −0·50) %; ER −1·56 (95 % CI −2·20, −0·92) %, $P=0·42$), participants in the LC group had greater reductions in the ratio of total cholesterol:HDL-cholesterol ($P=0·03$) and also in the ratio of TAG:HDL-cholesterol ($P=0·01$) than those in the ER group. The present 12-week diet trial suggested that both a LC non-energy-restricted diet and an ER diet were acceptable to Chinese women and both diets were equally effective in reducing weight and fat mass. Moreover, the LC diet showed beneficial effects on blood lipid profiles.

Key words: Low-carbohydrate diet: Overweight: Obesity: Randomised controlled trials

Obesity has become a major public health challenge not only in Western countries[1,2] but also in Asian countries, which are undergoing rapid changes in nutrition and lifestyle[3]. In China between 2002 and 2010, the prevalence of overweight and obesity in adults increased from 22·8 to 30·6 % and from 7·1 to 12·0 %, respectively[4,5]. This trend of rapid increase in excess body mass is expected to continue, particularly given the current obesogenic environment[6]. Thus, developing effective intervention strategies is critically important to control obesity and related cardiometabolic diseases.

In recent years, there has been growing interest as to whether low-carbohydrate (LC) diets are as effective as, or perhaps better than, traditional low-fat/low-energy diets for weight management; however, findings from various studies remain controversial[7,8]. In a systematic review including thirteen clinical trials, LC diets were found to be more effective in decreasing weight and TAG and increasing HDL-cholesterol than low-fat/low-energy diets[9]. A more recent review of seventeen interventions has shown that LC diets have favourable effects on major cardiovascular risk factors[10]. Similar results have also

Abbreviations: ER, energy-restricted; GGT, γ-glutamyl transferase; LC, low carbohydrate; UN, urea N.

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been suggested by a recent 2-year feeding trial in Israel[11]. However, inconsistent results have also been reported in another 2-year trial in which different diets yielded comparable reductions in weight[12] and fat mass[13], regardless of macronutrient composition.

To date, almost all published studies using LC diet interventions have been conducted among Western populations. Compared with Western diets, traditional diets in Asia tend to be high in carbohydrates. In China, although fat intake has increased from 22·0 to 29·8 % of energy intake in recent years[4], most people still consume a high-carbohydrate diet with an average intake of 321·2 g/d, accounting for 57 % of daily energy consumption[14]. A high intake of carbohydrates, especially white rice, has been shown to be positively associated with an increased risk of developing type 2 diabetes in the Shanghai Women's Health Study[15]. Given their habitually high carbohydrate consumption, it is unclear whether Chinese people are able to adapt to a LC diet for weight control. Therefore, the goal of the present study was to investigate the adherence to a LC diet on weight loss and its effects on the improvement of cardiovascular risk factors among overweight or obese Chinese women, in comparison with an energy-restricted (ER) diet.

Methods

Participants and study design

The present study was a randomised controlled feeding trial among female nurse assistants at a hospital in Shanghai. Eligible women were aged 30–65 years with a BMI ≥ 24 kg/m^2, the cut-off point for overweight in China[4]. Exclusion criteria included: (1) current pregnancy or lactation; (2) history of CVD, cancer or mental disorders; (3) clinically diagnosed gastrointestinal conditions that would prevent the participant from complying with the dietary restrictions of the trial; (4) having undergone gastrointestinal surgery previously (except for appendicitis or hernia); (5) current use of antidepressants; (6) plasma glutamic-pyruvic transaminase > 50 U/l; (7) plasma glutamic-oxaloacetic transaminase < 10 or > 35 U/l; (8) plasma creatinine < 30 or > 110 μmol/l; (9) urea N (UN) < 3·0 or > 7·5 mmol/l; (10) participating in other research studies within the 3 months before enrolment. We excluded those with liver and renal biomarkers beyond reference levels, because of concerns that a LC diet with high intakes of protein and fat might burden liver and/or renal function, particularly for individuals having abnormal levels of liver and renal biomarkers[16].

An introduction to the study was provided to potential participants (154 in total) by the centre of nurse assistants who were not affiliated with the hospital. Those who were interested in the study were invited to complete a screening questionnaire. After further checking their recent physical examination results, fifty-four subjects were eligible. Of these subjects, four withdrew from the study due to job-related or other personal reasons. A total of fifty female participants were successfully recruited and randomly assigned to either a LC diet or an ER diet group for 12 weeks. Randomisation was conducted by a statistician who was not involved in any other aspects of the study by using block randomisation, stratified by 10-year age categories. Although the participants were randomised by age, baseline BMI levels of the two groups were similar after randomisation. The study protocol was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects were approved by the Institutional Review Board of the Institute for Nutritional Sciences, Chinese Academy of Sciences. Written informed consent was obtained from all subjects. The present trial was registered at ClinicalTrials.gov as NCT01358 890 (http://clinicaltrials.gov/show/NCT01358 890).

Intervention

The LC diet was designed to provide 20 g carbohydrate daily in the first week, with a gradual increase to 120 g, by adding 10 g weekly until the 11th week, since carbohydrate intake up to 120 g/d has been reported to be sufficient to benefit weight control and metabolic profiles[11]. In addition, a ketogenic diet with no more than 50 g carbohydrate[17] might be rather difficult for a population with a habitually high carbohydrate intake. Carbohydrate-rich foods, such as white rice, steamed bread and tubers, were substituted with fish, poultry and plant oil. In addition to three meals, snacks, including boiled eggs (with or without yolk), cucumbers and tomatoes, were also provided *ad libitum* any time from 06.00 to 17.30 hours each day (Table S1, available online).

The ER diet was designed in the traditional Chinese style (Table S1, available online) with an initial target for a total energy intake of 5021 kJ/d (1200 kcal/d). During the first 3 d of the intervention, seven participants in the ER group reported extreme hunger, all of whom had previously been consuming a relatively high amount of energy (> 8368 kJ/d (2000 kcal/d) according to the 3 d food diary completed before the intervention). The targeted energy intake for those participants was adjusted to 6276 kJ/d (1500 kcal/d) by increasing their rice intake. On average, energy intake was 65 % of their usual daily intake. Energy from carbohydrate, protein and fat in the ER diet was 50–55, 17–19 and 26–33 %, respectively.

All experimental meals were prepared in a designated kitchen at the hospital. Foods were weighed using an electronic scale before cooking and meal preparations were supervised by a registered dietitian. All participants received their experimental meals every day including weekends. Participants were encouraged to consume every meal in a designated dining room within the building where they worked. Sometimes the participants also consumed meals close to their working place in the hospital if they had a short lunch break. In this case, the participants were required to report to dietitians about any leftovers or intake of foods other than the experimental meals. At the beginning of the intervention, participants were instructed to maintain their usual physical activity levels throughout the study; those in the LC diet group were particularly recommended to drink plenty of plain water, to compensate for possible water loss in ketosis.

Measurements

Information on demographic characteristics, lifestyle factors, health status, medication use and physical activity levels

(using the International Physical Activity Questionnaire, the short 7 d format) was collected using a standard questionnaire at baseline. Body weight was measured to the nearest 0·1 kg at the beginning and then biweekly during the trial using an electronic scale (Seca-882; ScalesGalore). Other anthropometric data described below were collected at baseline and at the end of the intervention. Height was measured to the nearest 0·1 cm using a portable stadiometer (Seca-214; ScalesGalore). Waist circumference was measured to the nearest 0·1 cm at the mid-point between the lowest rib and the iliac crest after inhalation and exhalation, while hip circumference was measured at the widest girth of the hip to the nearest 0·1 cm, with a plastic-coated fibreglass tape (Grafco Model 17-1340-2). Blood pressure was measured on the right arm, after at least 5 min of rest, using an electronic blood pressure monitor (Omron HEM-7000); three measurements were performed, and the last two were used in the analyses. Fat mass (percentage), lean mass and bone mineral density were measured by a whole-body dual-energy X-ray absorptiometry scan using a Hologic QDR 4500 W scanner (Hologic). Overnight fasting blood samples were collected at baseline and at the end of the intervention; urine samples were collected at weeks 0, 2, 4 and 12. Immediately after collection, all the samples were stored at −80°C until laboratory assays were conducted.

After the intervention, plasma concentrations of fasting glucose, TAG, total cholesterol, HDL- and LDL-cholesterol, glutamic-oxaloacetic transaminase, glutamic-pyruvic transaminase, γ-glutamyl transferase (GGT), creatinine, UN and uric acid were measured on an automatic analyser (Hitachi 7080) using commercial kits from Wako Pure Chemical Industries. At weeks 0, 2, 4 and 12, urinary ketones were qualitatively assayed on an automatic analyser (Urisys 1100) with reagents purchased from Roche Diagnostics.

Compliance

Dietary compliance was evaluated by using food diaries and measuring urinary ketones. Hunger levels and overall diet acceptance were assessed through self-reports. At baseline, intakes of energy and nutrients were obtained through a 3 d food diary[18]. It was completed by the participants and then was reviewed by the dietitians, and any missing data were filled in immediately after inquiring the participants. This food diary covered thirteen Chinese food categories, listed twenty-seven common food items and left space for unlisted food items. Portion size for each food item was specified by the participants. At weeks 6 and 12, intakes of energy and nutrients were evaluated through a combined analysis of meal menus (Table S1, available online) and a 7 d food diary recorded by a dietitian. Energy and nutrients were calculated using Nutrition Star Software (Zhending Company Limited), in accordance with the Chinese food composition table[19]. Participants were asked to report any side effects or discomfort to the dietitian. At the end of the intervention, a five-point Likert scale[20,21] was used to evaluate the hunger level at each month of the intervention. The retrospective data collection was designed to minimise potential psychological effects on weight loss behaviour by repeated assessments during the intervention[22]. At the end of the intervention, all participants were asked the following question: 'What was your hunger level at month 1, month 2 and month 3?', with – one- to five-point scale indicating 'not hungry at all, a little hungry, hungry, very hungry and extremely hungry'. Another five-point Likert scale was used to evaluate the overall acceptance of the assigned diets, by asking 'what is your overall acceptance of the assigned diet?', with – one- to five-point scale indicating 'unacceptable, indifferent, acceptable, quite acceptable and highly acceptable', respectively.

Statistical analyses

Analyses were performed based on the intention-to-treat principle. We estimated that seventeen participants in each group would provide 90 % power to detect a difference of 0·30 mmol/l of HDL-cholesterol between groups, assuming a standard deviation of 0·27 mmol/l, although the sample size limited our ability to detect differences in other outcomes. All variables were quantitative except for urinary ketone levels. Hunger levels and the overall acceptance of diets were treated as continuous variables. Changes in all variables were calculated by subtracting the baseline values from the values at the end of the trial. Within-group differences were analysed using paired *t* tests, and Wilcoxon signed-rank tests for skewed variables. Between-group differences in baseline data and dietary changes were calculated using Student's *t* tests or Wilcoxon–Mann–Whitney rank-sum tests for those skewed variables. Between-group differences for changes in body composition and metabolic biomarkers were evaluated using generalised linear models, including baseline age, BMI and physical activity (metabolic equivalents (MET)-min/d) as covariates. Pearson's correlation coefficient was used to assess correlations between changes in macronutrients and metabolic biomarkers. All statistics were performed using Stata (version 9.2), and a two-sided $P<0·05$ was considered as significant.

Results

Characteristics of the participants

A total of forty-eight participants completed the intervention. Of these, one participant dropped out of each group due to a busy schedule or for personal reasons (Fig. S1, available online). The mean age was 47·9 (SD 6·6) years and the mean BMI was 26·7 (SD 2·3) kg/m^2 for all participants. None of the subjects had a history of smoking or alcohol drinking. Participants in the two groups had comparable BMI, waist and hip circumferences, fat mass, lipid profiles and markers related to liver and renal function at baseline (Tables 1 and 2).

Diet acceptance and hunger level

Both groups had similar acceptability of the assigned diets (LC 2·84 (SEM 0·3) *v.* ER 3·04 (SEM 0·3), $P=0·605$) according to the five-point Likert scale. The hunger levels for months 1, 2 and 3 were 3·32 (SEM 0·3), 2·20 (SEM 0·2) and 1·68 (SEM 0·2) for the LC diet, respectively ($P<0·001$). The corresponding scores

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Table 1. Anthropometry and body composition variables during the intervention*
(Mean values with their standard errors and 95 % confidence intervals)

		Baseline			Week 12		Change from baseline				
Variables	Groups	Mean	SEM	*P*	Mean	SEM	Mean	95 % CI	Difference of change	95 % CI	*P*†
Weight (kg)	LC	64·8	1·3	0·234	59·5	1·2	−5·3	−6·1, −4·5	−0·2	−1·1, 0·7	0·666
	ER	67·0	1·3		61·2	1·1	−5·1	−5·5, −4·7			
BMI (kg/m^2)	LC	26·6	0·5	0·663	24·4	0·4	−2·2	−2·6, −1·8	−0·1	−0·5, 0·3	0·499
	ER	26·9	0·4		24·5	0·4	−2·1	−2·2, −1·9			
Waist circumference (cm)	LC	90·2	1·1	0·630	82·4	1·4	−7·9	−9·2, −6·5	−1·3	−3·5, 0·9	0·210
	ER	91·0	1·1		84·2	1·3	−6·5	−8·3, −4·7‡			
Hip circumference (cm)	LC	99·5	1·0	0·326	96·4	1·0	−3·1	−4·1, −2·1‡	0·4	−0·9, 1·7	0·497
	ER	100·8	0·9		97·0	0·9	−3·5	−4·3, −2·7‡			
Waist:hip ratio	LC	0·91	0·01	0·626	0·85	0·01	−0·05	−0·07, −0·04	−0·02	−0·04, 0·01	0·098
	ER	0·90	0·01		0·87	0·01	−0·04	−0·05, −0·02‡			
Systolic blood pressure (mmHg)	LC	134·0	3·4	0·582	113·7	2·0	−20·3	−24·8, −15·8	−4·6	−10·9, 1·7	0·124
	ER	131·4	3·4		116·4	2·6	−15·7	−20·4, −11·0			
Diastolic blood pressure (mmHg)	LC	86·5	1·6	0·679	75·7	1·5	−10·8	−13·0, −8·7	−2·8	−6·6, 1·0	0·197
	ER	85·5	2·0		77·7	2·0	−8·1	−11·3, −4·8			
Fat mass (kg)	LC	22·6	0·8	0·613	20·1	0·8	−2·48	−3·10, −1·85	0·11	−0·64, 0·86	0·769
	ER	23·1	0·8		20·1	0·7	−2·59	−3·02, −2·15			
Fat percentage	LC	34·9	0·7	0·734	33·7	0·8	−1·19	−1·88, −0·50	0·37	−0·55, 1·29	0·420
	ER	34·5	0·7		32·8	0·7	−1·56	−2·20, −0·92			
Lean mass (kg)	LC	41·8	0·7	0·111	39·2	0·7	−2·61	−3·12, −2·09	−0·40	−1·10, 0·29	0·225
	ER	43·5	0·7		41·0	0·6	−2·20	−2·69, −1·71			
Trunk fat mass (kg)	LC	11·9	0·5	0·494	10·6	0·4	−1·33	−1·76, −0·89	0·17	−0·36, 0·70	0·496
	ER	12·4	0·5		10·8	0·5	−1·50	−1·81, −1·18			
Leg fat mass (kg)	LC	6·84	0·28	0·727‡	6·08	0·28	−0·77	−0·97, −0·57	−0·10	−0·38, 0·19	0·459
	ER	6·97	0·31		6·07	0·21	−0·67	−0·88, −0·46			
Bone mineral density (g/cm^2)	LC	0·94	0·03	0·115	0·95	0·03	0·01	−0·01, 0·02	0·01	−0·01, 0·03	0·313
	ER	0·99	0·02		0·99	0·03	0·00	−0·02, 0·01			

LC, low carbohydrate; ER, energy-restricted.
* *n* 25 for both groups at baseline. *n* 25 for the LC group and *n* 24 for the ER group for the values at week 12 and the changes. Within-group changes are all significant ($P<0·05$), except for bone mineral density.
† Using the generalised linear model, adjusted for baseline age, BMI and physical activity.
‡ Wilcoxon signed-rank test for paired *t* test.

Table 2. Cardiometabolic risk factors and markers for liver and renal function during the intervention†
(Mean values with their standard errors and 95 % confidence intervals)

		Baseline			Week 12		Change from baseline				
Variables	Groups	Mean	SEM	*P*	Mean	SEM	Mean	95 % CI	Difference of change	95 % CI	*P*‡
Glucose (mmol/l)	LC	6·01	0·18	0·655	6·11	0·24	0·12	−0·52, 0·76	0·44	−0·37, 1·24	0·338
	ER	6·15	0·24		5·86	0·19	−0·32	−0·83, 0·20			
TAG (mmol/l)	LC	1·69	0·26	0·417§	0·79	0·07	−0·88*§	−1·37, −0·41	−0·44	−0·92, 0·04	0·078
	ER	1·33	0·12		0·90	0·11	−0·45*§	−0·57, −0·33			
Total cholesterol (mmol/l)	LC	5·01	0·21	0·567	5·00	0·25	0·01	−0·61, 0·62	0·69	−0·03, 1·42	0·075
	ER	5·19	0·24		4·55	0·16	−0·68*	−1·11, −0·26			
HDL-cholesterol (mmol/l)	LC	1·30	0·07	0·429§	1·45	0·07	0·16	−0·02, 0·34	0·30	0·08, 0·52	0·009
	ER	1·44	0·08		1·31	0·07	−0·14§	−0·27, −0·00			
LDL-cholesterol (mmol/l)	LC	3·30	0·16	0·596	3·35	0·23	0·05	−0·40, 0·50	0·56	0·01, 1·10	0·056
	ER	3·44	0·20		2·99	0·13	−0·50*	−0·84, −0·17			
Total:HDL-cholesterol ratio	LC	4·03	0·21	0·246	3·53	0·15	−0·50*	−0·77, −0·22	−0·34	−0·65, −0·04	0·027
	ER	3·72	0·16		3·61	0·16	−0·15§	−0·31, 0·00			
LDL:HDL-cholesterol ratio	LC	2·67	0·16	0·382	2·37	0·14	−0·31*	−0·54, −0·07	−0·18	−0·44, 0·08	0·158
	ER	2·48	0·15		2·39	0·14	−0·13§	−0·27, 0·01			
TAG:HDL-cholesterol ratio	LC	1·40	0·23	0·131§	0·60	0·08	−0·80*§	−1·17, −0·43	−0·52	−0·90, −0·13	0·011
	ER	1·02	0·13		0·74	0·11	−0·28*§	−0·42, −0·14			
GOT (U/l)	LC	28·1	1·2	0·977	28·3	1·1	0·3	−3·2, 3·8	1·6	−2·8, 6·0	0·582
	ER	28·1	1·5		26·7	1·4	−1·3§	−4·1, 1·6			
GPT (U/l)	LC	20·3	1·3	0·907	20·4	2·1	0·4§	−4·3, 5·1	3·4	−1·9, 8·9	0·286
	ER	20·1	1·7		17·1	1·4	−3·0*	−5·7, −0·3			
GGT (U/l)	LC	25·4	3·7	0·795§	21·0	4·2	−4·1*§	−9·9, 1·6	2·2	−4·3, 8·6	0·587
	ER	23·8	2·7		18·0	1·7	−6·3*	−9·6, −3·1			
Creatinine (μmol/l)	LC	53·2	1·9	0·106	60·7	2·7	8·2*	2·3, 14·1	3·1	−4·7, 10·9	0·528
	ER	57·7	2·0		63·2	2·2	5·1	−0·4, 10·5			
Blood urea N (mmol/l)	LC	5·0	0·1	0·789	6·6	0·3	1·6*§	0·9, 2·3	1·0	0·1, 1·9	0·027
	ER	5·1	0·3		5·7	0·2	0·6*	0·1, 1·2			
Blood uric acid (μmol/l)	LC	256·7	15·8	0·519	285·4	15·5	28·2*§	−11·0, 67·4	18·8	−25·2, 62·7	0·479
	ER	270·2	13·6		280·9	13·8	9·5	−13·1, 32·0			

LC, low carbohydrate; ER, energy-restricted; GOT, glutamic-oxaloacetic transaminase; GPT, glutamic-pyruvic transaminase; GGT, γ-glutamyl transferase.
* Mean values were significantly different with respect to baseline ($P<0·05$).
† *n* 24 for the LC group and *n* 25 for the ER group at baseline; *n* 25 for the LC group and *n* 24 for the ER group at week 12; *n* 24 for both groups for changes.
‡ Using the generalised linear model, adjusted for baseline age, BMI and physical activity.
§ Wilcoxon signed-rank test for paired *t* test.

were 3·12 (SEM 0·2), 2·37 (SEM 0·2) and 2·20 (SEM 0·2) for the ER diet, respectively ($P=0·004$). The between-group difference was statistically significant only at month 3 ($P=0·049$), but not at the other time points.

Dietary intake, physical activity and urinary ketones

Total energy and macronutrient intake at baseline were comparable in the two groups (Table 3). Throughout the study, the total energy intake decreased in both groups and was lower in the LC group (LC 4999·9 (SEM 6·7) kJ *v.* ER 5670·6 (SEM 26·8) kJ, $P<0·001$) at week 12. Carbohydrate intake also decreased in both groups (Table 3). As expected, participants in the LC group had a significantly lower carbohydrate intake at week 6 (23·4 (SEM 0·9) *v.* 50·9 (SEM 0·6) %, $P<0·001$) and week 12 (36·1 (SEM 0·3) *v.* 51·1 (SEM 0·7) %, $P<0·001$); they also consumed significantly higher protein, fat and cholesterol at weeks 6 and 12 when compared with those in ER group. On the other hand, participants in the ER group consumed more dietary fibre than those in the LC group (Table 3). During the intervention period, physical activity levels remained unchanged in the LC group, but increased significantly in the ER group (Table 3). The largest proportion (26·1 %) of participants having detectable urinary ketones occurred at week 2 in the LC group.

Anthropometry and body composition

No significant between-group difference in the amount of weight loss was detected during the intervention period (Fig. 1; Table 1), although weight reduction with the LC diet was greater than that with the ER diet at week 2 (LC −2·15 kg *v.* ER −1·60 kg; $P=0·047$). At the completion of the intervention, participants in both groups had significantly lower levels of weight, BMI, waist and hip circumferences, blood pressure, absolute fat mass (total, trunk and leg) and lean mass, and the percentage of fat mass (Table 1). However, no significant between-group difference was detected for any of these parameters.

Lipid profiles and fasting glucose

At the end of the 12-week intervention, plasma TAG and the ratio of TAG:HDL-cholesterol declined significantly in both groups (both $P<0·001$; Table 2). HDL-cholesterol tended to increase in the LC group, but to decrease in the ER group, and the change in HDL levels was significantly different between the two groups (0·16 *v.* −0·14 mmol/l, $P=0·009$). Moreover, women in the LC group also had greater reductions in the ratio of total cholesterol:HDL-cholesterol (−0·50 *v.* −0·15, $P=0·027$) and the ratio of TAG:HDL-cholesterol (−0·80 *v.* −0·28, $P=0·011$) than those in the ER group (Table 2). No significant difference for changes in fasting glucose and LDL-cholesterol was found between the two groups.

Liver and renal function markers

In comparison with baseline, the LC group had significantly lower GGT ($P=0·026$), but higher plasma creatinine ($P=0·009$), UN ($P<0·001$) and uric acid ($P=0·031$), while the ER group had significantly lower glutamic-pyruvic transaminase ($P=0·033$) and GGT ($P<0·001$), but higher UN levels ($P=0·022$) after the 12-week intervention. However, the between-group difference was statistically significant only for the change in UN ($P=0·027$).

Adverse events

Over the course of the intervention, participants reported several instances of discomfort and adverse events: stomach upset (LC *n* 8; ER *n* 8); leg cramps (LC *n* 5; ER *n* 1); dizziness or headache (LC *n* 4; ER *n* 1); toothache (LC *n* 4; ER *n* 0); constipation (LC *n* 4; ER *n* 5); diarrhoea (LC *n* 1; ER *n* 1); nausea (LC *n* 1; ER *n* 0). The vast majority (76 %) of these minor adverse events occurred in the first half of the intervention.

Discussion

In the present 12-week randomised controlled trial, we found that the LC diet was acceptable and effective in short-term weight loss in overweight and obese Chinese women, when compared with a high-carbohydrate, ER diet. In addition, the LC diet exhibited more favourable effects on HDL-cholesterol, total:HDL-cholesterol ratio and TAG:HDL-cholesterol ratio. The adherence to the two diets was similar. To our knowledge, this is the first feeding trial to determine the adherence to and the effects of a LC diet on weight loss in Asian populations.

Although rapid nutrition transition has been accompanied by reduced cereal consumption in recent decades, carbohydrates still contribute the majority of total energy intake in Asians[23–25]. For instance, carbohydrate consumption at baseline among our participants accounted for approximately 60 % of total energy (Table 3). A high carbohydrate intake, especially refined carbohydrates, has been linked to an increased risk of the metabolic syndrome and type 2 diabetes in several studies including women in Shanghai[15,26,27]. It remains unknown as to whether reducing carbohydrate intake is acceptable and effective for weight control in Asian populations. To date, only a few advice-based dietary interventions[28,29], rather than well-controlled feeding trials, have been conducted to test the effect of a LC diet on weight control in Asians. In the present trial, 96 % of the participants in both diet groups completed the intervention; 97·3 % of the provided experimental meals were completely consumed, 2·2 % were partially consumed and the remaining 0·5 % were not consumed by the participants. These results suggest that the intended intervention was substantially achieved and a LC diet was as acceptable as an ER diet in people with a habitually high carbohydrate intake. Urinary ketones were detected in 26·1 % of the participants in the LC group at week 2, and also in a few individuals in the ER group at weeks 4 and 12. Similarly, in a previous education-based intervention, which advocated less than 20 g/d of carbohydrate intake in diabetic patients, 29 % (five out of seventeen) of participants had urinary ketones greater than trace at week 2[30]. In another study, Shai *et al.*[11] also reported that urinary ketones were present among participants in low-fat and Mediterranean diet groups, when carbohydrate accounted for 50 % of their total energy. Given the fact that circulating ketone

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Table 3. Dietary intake, physical activity and urinary ketones by diet group and time point
(Mean values with their standard errors)

	LC group		ER group	
	Mean	SEM	Mean	SEM
Energy (kJ)				
Baseline	8427·4*	92·7	8780·1	75·7
Week 6‡	5045·5	5·4	5603·2	26·3
Week 12‡	4999·9	6·7	5670·6	26·8
Carbohydrate (g)				
Baseline	302·5*	17·1	332·1	14·6
Week 6	79·3	2·9	181·7	5·7
Week 12	117·2	1·2	184·6	6·0
Carbohydrate (% of total energy)				
Baseline	57·1*	1·6	61·0	1·3
Week 6	23·4	0·9	50·9	0·6
Week 12	36·1	0·3	51·1	0·7
Protein (g)				
Baseline	78·4*	4·4	77·9	3·9
Week 6	74·7†	1·1	58·6	0·8
Week 12	77·6†	0·4	59·9	0·9
Protein (% of total energy)				
Baseline	15·1*	0·4	14·7	0·5
Week 6	24·8	0·3	17·6	0·1
Week 12	26·0	0·1	17·7	0·1
Fat (g)				
Baseline	59·4*	3·4	59·3	3·4
Week 6	69·4	1·0	46·7	0·2
Week 12	50·4	0·3	46·6	0·1
Fat (% of total energy)				
Baseline	27·8*	1·4	24·3	1·1
Week 6	51·8	0·7	31·6	0·5
Week 12	37·9	0·2	31·2	0·6
SFA (g)				
Baseline	41·1	2·3	35·0	1·6
Week 6	40·2†	0·5	28·5	0·1
Week 12	27·8	0·2	28·4	0·1
Unsaturated fatty acids (g)				
Baseline	21·0*	1·9	20·6	1·7
Week 6	28·3	0·4	17·7†	0·1
Week 12	21·9†	0·2	17·7†	0·1
MUFA (g)				
Baseline	9·1*	0·8	8·9	0·7
Week 6	11·5	0·2	7·5	0·1
Week 12	9·6	0·1	7·5	0·1
PUFA (g)				
Baseline	12·0*	1·1	11·7	1·0
Week 6	16·8	0·3	10·1†	0·l
Week 12	12·3†	0·1	10·2†	0·1
Cholesterol (mg)				
Baseline	330·5*	27·4	280·7	33·6
Week 6	532·0	19·1	401·0	1·9
Week 12	599·7	12·9	411·7	3·1
Fibre (g)				
Baseline	11·5*	0·9	11·4	0·7
Week 6	8·9	0·1	10·7†	0·2
Week 12	9·5	0·1	10·8†	0·2
Physical activity level (MET-min/d)				
Baseline	683	77	615	63
Week 12	782†	73	903	71
Detectable urinary ketones§				
Baseline				
Participants (*n*)	0		0	
%				
Week 2				
Participants (*n*)	6		0	
%	26·1			
Week 4				
Participants (*n*)	2		1	
%	8		4·2	
Week 12				
Participants (*n*)	1		4	
%	4		16·7	

LC, low carbohydrate; ER, energy-restricted; MET, metabolic equivalents.
* Mean values were not significantly different from the ER group in a row ($P > 0·05$).
† Mean values were not significantly different from baseline in a column ($P > 0·05$).
‡ The number of subjects are twenty-five in both groups at baseline, twenty-four in the ER group at week 6 and twenty-four in both groups at week 12, unless otherwise noted.
§ The number of subjects varied because of menopause inconvenience (LC: *n* 25 at baseline, week 4 and week 12, *n* 23 at week 2; ER: *n* 24 at baseline and week 12, *n* 22 at week 2, *n* 23 at week 4).

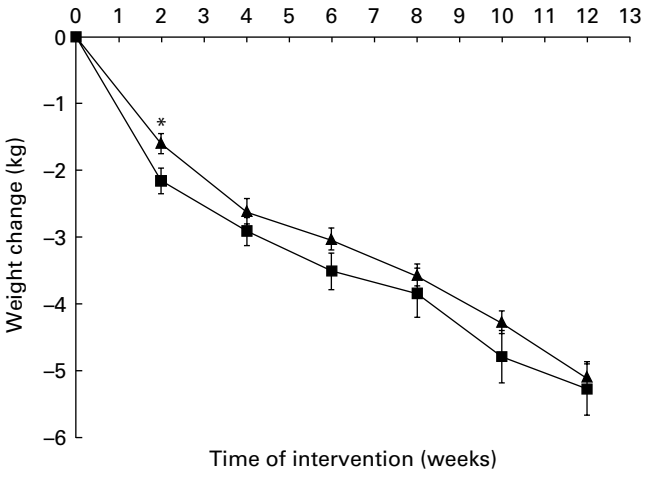

Fig. 1. Weight change during the intervention. ■, Low-carbohydrate group; ▲, energy-restricted group. Values are means, with their standard errors represented by vertical bars. * Mean value was significantly different from that of the low-carbohydrate group ($P<0·05$).

levels could be influenced by fasting status, prolonged exercise or having a ketogenic diet[31], it is possible that urinary ketones might not exclusively reflect compliance with a LC diet.

It is well known that feeling hungry is one of the major challenges for adhering to an ER diet. Interestingly, participants on the ER diet showed a reduced hunger level towards the end of the intervention, although not as dramatic as those on the LC diet. Nickols-Richardson *et al.*[32] also observed a trend of declining hunger level in a high-carbohydrate, ER diet group, though not significant. It is possible that participants adapted to the ER diet gradually. For those in the LC group in the present trial, the reduced hunger level might partially explain the lower energy intake at week 12.

The present results suggest that the LC diet was as effective as the ER diet in reducing weight and fat mass throughout the intervention (Fig. 1), consistent with the findings from previous intervention studies conducted in Western populations[12,13]. Participants on the LC diet had significantly greater weight loss than their ER counterparts at week 2 when starchy staple foods were prohibited in the LC diet (carbohydrate ≤30 g/d; Table S1, available online), and 26·1 % of them had detectable urinary ketones. Therefore, the initial weight reduction in the LC diet group might be partly due to the loss of water during the mobilisation of glycogen from the liver and the filtration of ketone bodies by the kidney[33]. It is also possible that the ketogenic LC diet accelerates lipolysis by switching fuel sources from glucose to ketone bodies[34,35]. In the present study, participants in both diet groups also showed similarly reduced fat mass and lean mass over the 12-week intervention (Table 1), although it has been suggested that a LC diet with a relatively high protein intake may lead to a greater loss of fat mass[36], while preserving lean mass[37], when compared with conventional diets. The discrepancies between the present study and others may be due to the differences in study design, sample size and components of the intervention diets.

Similar to the findings from the trials in Western countries[11,38], the present data also showed beneficial effects of the LC diet on elevating HDL-cholesterol and reducing the ratio of TAG:HDL-cholesterol. This finding is particularly important for Chinese women who tend to have a higher prevalence of low HDL-cholesterol compared with American women[39,40]. It is noteworthy that changes in HDL-cholesterol in the two diet groups went in opposite directions, even with similar amounts of weight loss, suggesting an independent role of macronutrient proportions in a given diet[41], although none of the correlations between the changes in macronutrients and HDL-cholesterol was significant ($P=0·22$, 0·77 and 0·75 for carbohydrate, protein and fat, respectively). It still remains unclear as to the underlying mechanism(s) in this regard, although limited data from animal studies suggest that lipoprotein lipase might play an important role. Carbohydrate restriction has been hypothesised to increase circulating TAG-rich chylomicrons which might induce the activity of lipoprotein lipase. Enhanced lipoprotein lipase activity may mediate the lipolysis of VLDL and consequently release unesterified cholesterol, phospholipid, apoE, apoC-II and apoC-III to form mature HDL-cholesterol[42]. Obviously, biological pathways involving the effect of a LC diet on HDL-cholesterol require further research.

Whether a higher fat and protein intake in a LC diet would affect hepatic and renal functions has been a concern[16,43]. In the present study, plasma UN levels were significantly higher in the LC group than in the ER group. It resembles the finding from a previous randomised trial conducted by Yancy *et al.*[44], in which circulating UN increased more in a LC group (initial carbohydrate intake <20 g/d) than in a low-fat group (<30 % of energy from fat, 2092–4184 kJ/d (500–1000 kcal/d) deficit) at the end of a 6-month intervention. The increased UN may be a reflection of a higher intake of dietary protein in a LC diet[45]. On the other hand, no between-group differences were found for changes in liver enzymes including glutamic-oxaloacetic transaminase, glutamic-pyruvic transaminase and GGT. Interestingly, compared with baseline, both diets significantly reduced plasma GGT, which might be explained by the decreased BMI, improved blood pressure and improved TAG in both groups[46].

The strengths of the present study include the randomised design with controlled feeding, the low dropout rate and the high compliance to the diets. There are limitations in the present study including: (1) the small sample size and the short trial duration limited the power to detect between-group differences, time × group interactions in weight and body composition as well as some of the metabolic markers; (2) only Chinese females were included, and it is unclear whether the results could be generalised to men and other ethnic groups; (3) the strictly controlled feeding design may not be generalised to those of free-living people.

In conclusion, in overweight and obese Chinese women, the LC and ER diets had similar acceptability and compliance, and resulted in similar reductions in body weight and fat mass during the 12-week intervention. Moreover, the LC diet demonstrated a more favourable change in the lipid profile. Further studies with larger sample sizes and longer durations of intervention are needed to examine the long-term effects of LC diets in populations with a habitually high carbohydrate intake.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0007114513000640

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