Soltani *et al. BMC Endocrine Disorders* (2025) 25:62
https://doi.org/10.1186/s12902-025-01878-4

BMC Endocrine Disorders

RESEARCH

Open Access

Adherence to low carbohydrate diet is inversely associated with metabolic syndrome: evidence from MASHAD study

Sanaz Soltani[1,2], Glareh Koochakpoor[3], Melika Gharizadeh[4], Simin Rashidian Yazd[2], Maryam Mohammadi-Bajgiran[2], Alireza Ghajary[2], Ali Zeyqami[2], Gordon A. Ferns[5] and Majid Ghayour-Mobarhan[2,6*]

Abstract

Background We studied the link between adherence to a low carbohydrate diet (LCD) and metabolic syndrome (MetS) and its components in Iranian population.

Methods In this cross-sectional study, a validated 65-item food frequency questionnaire was used to collect dietary intakes from 3847 Iranian adults aged 35 to 65 years. These intakes were then used to calculate the LCD scores. The definition of metabolic syndrome followed the guidelines provided by the American Heart Association/National Heart, Lung and Blood Institute (AHA/NHLBI). To explore the association between LCD and MetS, multivariate logistic regression was employed in three models.

Results After accounting for potential confounding factors, individuals in the highest quartile of LCD score demonstrated a lower probability of having MetS compared to those in the lowest quartile (OR: 0.70; 95% CI: 0.56–0.88). When the analyses were performed for components of MetS, we found that compared to individuals in the bottom quartile, those in the top quartile of LCD score had a lower odds of enlarged waist circumference (OR: 0.62; 95% CI: 0.49–0.79), low serum HDL cholesterol (OR: 0.75; 95% CI: 0.62–0.92) and elevated blood pressure (OR: 0.71; 95% CI: 0.57–0.88). Regarding other components of MetS, no significant association was seen between LCD score and high serum triacylglycerol concentrations and abnormal glucose homeostasis.

Conclusions We found that adherence to a LCD was inversely related to MetS and its components including low serum HDL-C, elevated blood pressure, and enlarged waist circumference.

Clinical trial number Not applicable.

Keywords Cross-sectional, Iran, Low carbohydrate diet, Metabolic syndrome

*Correspondence:
Majid Ghayour-Mobarhan
ghayourm@mums.ac.ir
[1]Department of Nutritional Sciences, School of Health, Mazandaran University of Medical Sciences, Sari, Iran
[2]International UNESCO Center for Health-Related Basic Sciences and Human Nutrition, Mashhad University of Medical Sciences, Mashhad, Iran
[3]School of Nursing and Allied Medical Sciences, Maragheh University of Medical Sciences, Maragheh, Iran
[4]Student Research Committee, School of Paramedical and Rehabilitation Sciences, Mashhad University of Medical Sciences, Mashhad, Iran
[5]Devision of Medical Education, Brighton & Sussex Medical School, Falmer, Brighton, Sussex, UK
[6]Metabolic Syndrome Research Center, School of Medicine, Mashhad University of Medical Sciences, P.O. Box 99199-91766, Mashhad, Iran

Background

Metabolic syndrome (MetS), characterized by the concomitant occurrence of a cluster of cardio-metabolic risk factors including dysglycemia, hypertension, dyslipidemia, and abdominal obesity [1, 2], exhibits substantial global variation in prevalence, with estimates ranging from 12.5 to 31.4% depending on the specific criteria used in its definition [3]. In Iran, the overall prevalence of metabolic syndrome was found to be 30.4% [4]. This disorder is responsible for substantial health and socioeconomic costs worldwide mainly because of its resulting morbidity and mortality from chronic diseases including type 2 diabetes mellitus (T2DM), obesity, cancer, and cardiovascular disease (CVD) [5]. Therefore, prevention and management of MetS is of great priority for health care systems [6].

Lifestyle modifications such as diet and physical activity have been proposed as the effective strategies to control each component of MetS [7]. There is no consensus on the effective diet on all clinical indicators of metabolic syndrome and finding the best dietary approach to combat this heterogeneous disease has been a topic of interest for many researchers. Among various dietary patterns low carbohydrate diet (LCD) has received great attention [8]. Although this type of diet has been known as the first approach in diabetes management, several studies have reported its positive effects on the management of a range of non-communicable diseases including neurological disorders, obesity and various cancers [9]. Previous studies evaluated the metabolic effects of restricting carbohydrate cosumption in metabolic syndrome and its components and reported contradictory results. Some epidemiological studies reported that adherence to LCD had a significant protective role against MetS and its components [10–12]; while others failed to find such associations [13, 14]. These inconsistent findings make it difficult to conclude whether adoption of LCD is associated with improvement in metabolic syndrome or not. Investigating the effects of LCD on MetS has also been carried out by some interventional studies [15]. Findings of a recent meta-analysis showed that reduced intake of carbohydrate and increased intake of protein and fat result in improvement in markers of MetS in obese subjects free of CVD and T2DM [15]. It is worth noting that clinical trials determine the efficacy of a high dose intervention in a limited period of time; therefore, results of such studies cannot be necessarily extrapolated to people's routine life. In order to explore the relation of daily carbohydrate consumption in routine life with the risk of MetS, observational studies are needed. This is especially relevant in Middle-East countries where refined grains (such as white bread and white rice) are the staple foods [16]. Considering the aforementioned context, our study was performed to examine the relationship between adherence to LCD and MetS and its components among Iranian adults.

Materials and methods

Study population

In this cross-sectional study, data was collected from 9704 individuals aged 35 to 65 years who participated in the Mashhad stroke and heart atherosclerosis disorder (MASHAD) study, a prospective cohort study to assess 10-year cardiovascular risk among the population of the study. The study protocol has been previously described in detail [17]. Of the 9704 participants in the initial phase of the MASHAD study, dietary information was collected for 6696 people. In the current research, subjects who had a prior history of chronic illnesses (including hypertension, dyslipidemia and diabetes), those with missing data on dietary intake and metabolic syndrome and women with pregnancy and lactation were excluded. Moreover, individuals who reported total energy intakes outside the range of 800–4200 kcal/day were excluded. After these exclusions, 3847 participants were left for the final analyses. All participants were fully informed about the study and provided written consent. The study protocol received ethical approval from the Ethics Committee of Mashhad University of Medical Sciences (MUMS), Mashhad, Iran (Ethics code: IR.MUMS.REC.1386.250).

Dietary intake and LCD assessment

The participants' dietary intake was evaluated using a validated 65-item semi-quantitative food frequency questionnaire (FFQ) [18]. A certified Nutritionist administered the FFQ during a face-to-face interview to all participants. The questionnaire included 65 food items commonly consumed by Iranian people, with standard portion sizes. Participants were required to indicate their intake for each food item based on five-choice frequency response categories [18]. To analyze micro- and macronutrient intake, we used Diet Plan 6 software (Forestfield Software Ltd., Horsham, West Sussex and UK) which was modified for Iranian traditional foods by utilizing the nutrient composition of Iranian foods. The LCD score in the current study was calculated based on deciles of energy percentages from fats, proteins, and carbohydrates, for all enrolled subjects. A value of 10 was assigned to individuals who were in the lowest decile of carbohydrate intake and those who were in second decile were assigned a value of 9 and so on down to subjects who were in the highest decile were assigned a value of 1. A reverse method was used for scoring of fat and protein intakes; such that participants in the top decile were assigned the value of 10 and those in the bottom decile received the value of 1. The overall LCD score was then obtained by summing the scores for the three macronutrients that ranged from 3 to 30. Therefore, a higher LCD score implies a greater adherence to the LCD pattern.

Blood sampling and biochemical analyses

To measure high density lipoprotein cholesterol (HDL-C), triglycerides (TGs), and fasting blood glucose (FBG) at the beginning of the study, a 12-hour fast was required, and a blood sample was obtained from each participant. We used commercial kits and an Alycon auto analyzer (ABBOTT, Chicago, IL, USA) to analyze the samples.

Definition of metabolic syndrome

Metabolic syndrome was defined according to the recommendations of the American Heart Association/National Heart, Lung and Blood Institute (AHA/NHLBI) guideline [19]. It was considered present if a participant had at least three of the following five metabolic abnormalities: (1) low serum HDL-C (< 50 mg/dL in women and < 40 mg/dL in men); (2) abnormal glucose homeostasis (fasting plasma glucose concentration ≥ 100 mg/dL); (3) elevated levels of serum triacylglycerol (≥ 150 mg/dL); and (4) high blood pressure (≥ 130/85 mm Hg); and (5) enlarged waist circumference (WC) (≥ 91 cm for Iranian women and ≥ 89 cm for Iranian men [20]).

Baseline characteristic assessment

General characteristics of research subjects including gender, age, education, smoking status, marital status, anthropometric data (including weight, height, and WC) and blood pressure were assessed by two professional health care providers and a qualified nurse through interview and examination as previously described [21]. We computed body mass index (BMI) by dividing weight in kilograms by height in meters squared. Physical activity level (PAL) was determined by using a validated questionnaire as detailed before [22]. The questionnaire was structured into three sections: one focused on work-related activities, another on leisure activities, and the last one on time spent in bed. The integrated energy index (IEI) ranged from 1.61 during periods of inactivity to 4.39 during active periods.

Statistical analysis

Continuous variables were tested for normal distribution using histogram charts and Kolmogorov-Smirnov tests. Since the distribution of the continuous variables were skewed, medians and interquartile ranges (IQR) were used to describe these variables. We classified participants based on quartile categories of LCD scores. Where appropriate, Chi-square test and Kruskal-Wallis test were used to compare general characteristics and dietary intakes of study participants across quartiles of LCD scores. To examine the association between LCD scores and MetS we used binary logistic regression in different levels of adjustments. Sex (man/woman) and age (continuous) were adjusted in the first model. Additional adjustment was carried out for educational level (non-university education/university graduated), marital status (divorced/single/married), smoking status (non-smoker/smoker), physical activity (continuous), and total energy intake (continuous) in the second model. Finally, further adjustments were made for BMI (continuous). All confounding variables were chosen based on literature [23, 24]. We considered the first quartile of LCD scores as the reference category in all models. To determine *P* for trends, quartiles of the LCD scores were considered as ordinal variable in the analysis. All analyses were conducted using SPSS software (version 19.0; SPSS Inc, Chicago IL). *P*-value less than 0.05 was used as a threshold of significance.

Results

Metabolic syndrome was prevalent among 28% (*n* = 1086) of the study population. The median (IQR) LCD score was 16.0 (11.0-21.7). The study population had a mean (SD) age of 46.5 (7.87) and a mean (SD) BMI of 27.2 (4.72). Table 1 presents the general characteristics of

Table 1 Characteristics of study participants across categories of low-carbohydrate diet (LCD) score*

	Quartiles of LCD score				$P^{\dagger}$
	Q1	Q2	Q3	Q4	
Number of participants	946	1018	920	963	
Number of participants with MetS	282	327	231	246	
Age (year)	45.0 (40.0–51.0)	46.0 (40.0–52.0)	46.0 (40.0–52.0)	46.0 (40.0–52.0)	0.381
BMI (kg/m^2)	26.6 (23.3–29.8)	26.8 (23.8–29.9)	26.8 (24.1–29.9)	27.3 (24.6–30.4)	0.003
Physical activity	1.5 (1.4–1.7)	1.5 (1.4–1.7)	1.6 (1.4–1.7)	1.6 (1.4–1.7)	0.411
Female (%)	53.1	54.1	54.4	61.2	0.001
Married (%)	94.9	93.5	94.0	95.5	0.330
Education (university graduated) (%)	6.2	9.2	15.0	15.0	< 0.001
Current smokers (%)	30.6	22.4	20.8	15.3	< 0.001

*Data are presented as median (IQR) for continuous variables and percent for categorically distributed variables; †Kruskal-Wallis test for continuous variables and Chi-squared test for categorical variables

Table 2 Distribution of subjects with metabolic syndrome and its components across different quartiles of LCD score

	Quartiles of LCD score				$P^{\dagger}$
	Q1	Q2	Q3	Q4	
Number of participants	946	1018	920	963	
Number of participants with MetS	282	327	231	246	
Metabolic syndrome (%)	29.8	32.1	25.1	25.5	0.001
High serum triacylglycerol (%)	25.5	25.2	24.8	24.4	0.950
Enlarged waist circumference (%)	61.6	64.5	60.1	58.1	0.027
Elevated blood pressure (%)	30.1	29.8	22.9	25.7	0.001
Low serum HDL cholesterol (%)	64.4	63.6	62.5	60.1	0.240
Abnormal glucose homeostasis (%)	9.6	9.9	10.0	11.4	0.550

†Obtained by Chi-squared test

Table 3 Dietary intakes of study participants across quartile categories of LCD score *

	Quartiles of LCD score				P
	Q1	Q2	Q3	Q4	
Food groups					
Fruits (g/d)	168.6 (67.7-337.1)	177.1 (80.0-320.0)	187.1 (97.2–320.0)	177.1 (94.3-282.9)	0.438
Vegetables (g/d)	132.8 (84.4-202.3)	156.8 (97.2-242.6)	181.5 (107.5-278.3)	209.6 (135.1-304.7)	< 0.001
Dairy products (g/d)	237.3 (152.7-353.1)	298.4 (197.8-423.3)	342.5 (231.7-468.5)	404.6 (271.0-540.2)	< 0.001
Grains (g/d)	419.6 (326.3-550.3)	393.7 (294.8-476.6)	318.1 (249.8-404.8)	274.7 (209.8-344.2)	< 0.001
Meats (g/d)	58.0 (43.1–78.2)	78.7 (59.2-102.3)	90.6 (67.5-115.3)	115.8 (86.6-158.3)	< 0.001
Sugar sweetened beverages (g/d)	35.7 (8.3-107.1)	35.7 (8.3–79.7)	23.0 (8.3–79.7)	22.9 (8.3–71.4)	< 0.001
Added sugars (g/d)	50.0 (30.5–75.9)	37.5 (30.0-54.3)	30.2 (17.1–45.0)	20.5 (10.2–30.5)	< 0.001
Nutrients					
Total energy (kcal/d)	2086.1 (1699.6-2459.3)	2002.9 (1683.9-2406.3)	1986.1 (1635.0-2394.3)	1947.4 (1598.6-2369.2)	0.002
Carbohydrate (g/d)	334.0 (269.1-398.7)	294.0 (245.4-349.1)	266.8 (220.3-318.9)	231.0 (188.9-281.8)	< 0.001
Carbohydrate (% energy/d)	63.7 (61.9–66.1)	58.3 (57.1–59.6)	53.8 (52.2–55.2)	48.2 (44.9–50.6)	< 0.001
Protein (g/d)	67.5 (55.3–80.6)	72.3 (59.8–85.8)	73.8 (61.2–87.1)	79.7 (65.1–95.6)	< 0.001
Fat (g/d)	51.5 (40.8–62.1)	60.6 (49.8–74.7)	68.7 (54.7–86.5)	76.7 (61.4–97.6)	< 0.001
Dietary fiber (g/d)	27.0 (19.4–33.8)	26.5 (19.4–33.5)	24.7 (18.8–30.6)	22.2 (17.7–28.6)	< 0.001
Saturated fat (g/d)	22.3 (16.8–27.2)	26.5 (21.4–33.9)	30.9 (24.3–39.7)	35.3 (27.5–44.7)	< 0.001
Cholesterol (mg/d)	156.0 (119.7-199.2)	195.7 (151.8-246.1)	215.8 (171.6-278.8)	251.9 (197.4-316.6)	< 0.001
MUFA (g/d)	18.7 (14.7–23.9)	21.9 (17.5–28.0)	25.6 (20.0-34.9)	28.4 (22.2–38.0)	< 0.001
PUFA (g/d)	7.4 (6.0–9.0)	8.2 (6.7–9.9)	8.6 (7.0-10.6)	9.0 (7.4–10.9)	< 0.001
Vitamin C (mg/d)	131.8 (77.1-222.1)	141.9 (88.4–233.0)	160.7 (105.5-238.1)	167.9 (116.4-236.5)	< 0.001
Riboflavin (mg/d)	1.3 (1.0-1.7)	1.5 (1.1–1.8)	1.6 (1.3–1.9)	1.7 (1.4–2.1)	< 0.001
Selenium (mcg/d)	47.3 (38.3–58.1)	49.2 (39.2–60.3)	47.7 (38.4–58.6)	48.6 (38.9–60.0)	0.019
Calcium (mg/d)	849.6 (649.7-1087.4)	887.4 (677.0-1113.7)	896.2 (709.7–1122.0)	944.6 (742.3-1141.2)	< 0.001
Phosphorus (mg/d)	1205.0 (973.1-1441.5)	1282.5 (1016.2-1543.5)	1307.7 (1055.8-1539.9)	1337.6 (1103.7-1606.6)	< 0.001

*Obtained by Kruskal-Wallis test

study participants across quartiles of LCD score. Compared to those in the first quartile, participants in the fourth quartile of LCD score had higher BMI, were more likely to be female and university graduated and less likely to be current smoker. No significant difference was observed in terms of other variables.

The distribution of subjects with MetS and its components in various quartiles of LCD score is provided in Table 2. MetS, enlarged waist circumference, and elevated blood pressure were less frequent in the top quartile of LCD score compared to the bottom quartile. However, regarding other components of MetS, we found no significant difference across quartiles of LCD score.

Table 3 indicates the dietary intakes of participants across quartiles of LCD score. Higher adherence to LCD score was related to greater intakes of dairy products, vegetables, meats, protein, fat, saturated fat, cholesterol, monounsaturated fatty acid, polyunsaturated fatty acid, vitamin C, riboflavin, selenium, calcium and phosphorus and lower intakes of grains, sugar sweetened beverages, added sugars, total energy, carbohydrate and dietary fiber.

Table 4 demonstrates the crude and multivariable-adjusted odds ratios and 95% CIs for MetS and its components across quartiles of LCD score. In the crude model, comparing highest vs. lowest quartile, we found

Table 4 Multivariable-adjusted odds ratios (95% CIs) for metabolic syndrome and its components across quartile categories of LCD score

	Quartiles of LCD score				*P* trend
	Q1 (*n* = 946)	Q2 (*n* = 1018)	Q3 (*n* = 920)	Q4 (*n* = 963)	
LCD, median (IQR)	7 (5–9)	14 (12–15)	19 (18–20)	25 (23–27)	
Metabolic syndrome					
Crude	1.00	1.11 (0.92–1.35)	0.78 (0.64–0.96)	0.80 (0.66–0.98)	0.002
Model 1[†]	1.00	1.10 (0.91–1.34)	0.77 (0.62–0.94)	0.80 (0.65–0.98)	0.002
Model 2[‡]	1.00	1.07 (0.88–1.31)	0.75 (0.60–0.93)	0.76 (0.62–0.95)	0.001
Model 3[§]	1.00	1.06 (0.86–1.31)	0.71 (0.57–0.89)	0.70 (0.56–0.88)	< 0.001
Enlarged waist circumference					
Crude	1.00	1.13 (0.94–1.36)	0.93 (0.78–1.13)	0.86 (0.72–1.03)	0.032
Model 1	1.00	1.12 (0.93–1.35)	0.92 (0.76–1.11)	0.85 (0.71–1.03)	0.025
Model 2	1.00	1.08 (0.89–1.32)	0.89 (0.73–1.10)	0.81 (0.66–0.99)	0.011
Model 3	1.00	1.01 (0.80–1.28)	0.77 (0.60–0.97)	0.62 (0.49–0.79)	< 0.001
Low serum HDL cholesterol					
Crude	1.00	0.96 (0.80–1.16)	0.92 (0.76–1.11)	0.83 (0.69-1.00)	0.048
Model 1	1.00	0.96 (0.80–1.16)	0.91 (0.75–1.11)	0.78 (0.64–0.94)	0.010
Model 2	1.00	0.94 (0.78–1.15)	0.90 (0.74–1.09)	0.77 (0.63–0.93)	0.007
Model 3	1.00	0.94 (0.77–1.14)	0.89 (0.73–1.08)	0.75 (0.62–0.92)	0.005
Elevated serum triacylglycerol concentrations					
Crude	1.00	0.98 (0.80–1.20)	0.96 (0.78–1.18)	0.94 (0.76–1.16)	0.556
Model 1	1.00	0.98 (0.80–1.20)	0.96 (0.77–1.18)	0.97 (0.78–1.19)	0.733
Model 2	1.00	0.97 (0.79–1.20)	0.96 (0.78–1.20)	0.97 (0.78–1.20)	0.805
Model 3	1.00	0.96 (0.78–1.19)	0.95 (0.77–1.19)	0.94 (0.75–1.16)	0.581
Elevated blood pressure					
Crude	1.00	0.98 (0.81–1.19)	0.69 (0.56–0.84)	0.80 (0.65–0.98)	0.002
Model 1	1.00	0.96 (0.79–1.17)	0.64 (0.52–0.80)	0.78 (0.63–0.96)	0.001
Model 2	1.00	0.93 (0.76–1.13)	0.63 (0.50–0.78)	0.75 (0.60–0.92)	< 0.001
Model 3	1.00	0.92 (0.75–1.13)	0.61 (0.49–0.76)	0.71 (0.57–0.88)	< 0.001
Abnormal glucose homeostasis					
Crude	1.00	1.03 (0.76–1.39)	1.04 (0.77–1.41)	1.21 (0.90–1.63)	0.199
Model 1	1.00	1.02 (0.75–1.38)	1.02 (0.75–1.39)	1.19 (0.89–1.60)	0.248
Model 2	1.00	0.99 (0.73–1.34)	1.00 (0.73–1.36)	1.17 (0.86–1.58)	0.296
Model 3	1.00	0.99 (0.73–1.34)	0.99 (0.72–1.35)	1.15 (0.85–1.56)	0.359

[†]Model 1: Adjusted for age and sex

[‡]Model 2: Further adjusted for marriage status, education, smoking, physical activity, and total energy intake

[§]Model 3: Further adjusted for BMI

a significant inverse relationship between LCD score and MetS (OR: 0.80; 95% CI: 0.66–0.98). After adjustment for sex, age, marriage status, education, smoking, physical activity, and total energy intake, individuals in the fourth quartile of LCD score had a lower likelihood of MetS than those in the first quartile (OR: 0.76; 95% CI: 0.62–0.95). This inverse association remained significant even after further adjusting for BMI (OR: 0.70; 95% CI: 0.56–0.88).

When the analyses were performed for components of MetS, we observed that compared to individuals in the bottom quartile, those in the top quartile of LCD score had a lower odds of low serum HDL cholesterol (OR: 0.75; 95% CI: 0.62–0.92), enlarged waist circumference (OR: 0.62; 95% CI: 0.49–0.79), and elevated blood pressure (OR: 0.71; 95% CI: 0.57–0.88) after accounting for potential confounders. Regarding other components of MetS, no significant relationship was found between LCD score and abnormal glucose homeostasis as well as high serum triacylglycerol concentrations either before or after controlling for covariates.

Discussion

Results of the current study presented that adopting a LCD significantly decreased the risk of MetS and most of its components including low serum HDL-C, enlarged waist circumference, and elevated blood pressure. This significant relationship persisted even after adjustment for a range of potential confounders.

Few studies examined the relation between adherence to a LCD and MetS and reported inconsistent results [10, 13, 25, 26]. In line with our findings, Sangsefidi et al.

found that greater adherence to LCD was inversely associated with the risk of MetS and some of its components including abdominal obesity and low HDL-C, especially in men [10]. The same results were reported in a cohort study conducted by Mirmiran et al., which adherence to a LCD reduced the risk of MetS and inversely associated with some of its components including TGs, FBG, BP, and WC-BMI [11]. In contrast to our results, in a study conducted by Shirani et al., diets with lower amounts of carbohydrate were not related to the risk of MetS [25]. It is worth mentioning that the degree of carbohydrate restriction in the present study is different from that reported by Shirani et al. In our study, participants received nearly half of their required energy from carbohydrate (47.2%); while in the study of Shirani et al., carbohydrate intake was more limited, and participants in the fourth quartile of LCD consumed one third of their energy requirements from carbohydrate (36.0%). It is well known that high consumption of total fat is a risk factor for MetS [27]. Therefore, higher fat intake, following adherence to a LCD, might reduce the benefits of carbohydrate restriction. Moderate substitution of dietary fats for carbohydrates on the other hand seems to be a better strategy to combat MetS. Another study performed by Eslamian et al. on children and adolescents, reported no significant association between LCD and the incidence of MetS or its components [14]. It should be noted that the mentioned study has been done on a different age group (children and adolescents) for whom there is no reference value for different components of MetS. Therefore, their findings may not be comparable to the current study.

The present study found a significant inverse association between LCD score and risk of enlarged waist circumference, low serum HDL-C and elevated blood pressure. Contradictory findings have been reported on the association between LCD score and risk of components of MetS. Some studies showed a beneficial role of this diet on the risk of MetS components [13, 28], while others reported non-significant or even positive relations of LCD with the risk of components of MetS [29, 30]. It is worth mentioning that the type of fat and protein sources as well as the type of carbohydrate restricted in this diet may affect the risk of MetS components [31]. In the present study, participants in the highest quartile of LCD scores exhibited significantly greater intakes of mono- and polyunsaturated fatty acids compared to those in the lowest quartile. These increased levels of unsaturated fats may play a beneficial role in mitigating the risk of MetS and its components, possibly contributing to the observed reduction in risk associated with a low carbohydrate diet [32]. There is a paucity of data on the type and percentage of consumed fat, protein and carbohydrate in LCD which limits the ability to compare results across studies. Therefore, future studies on the association between LCD and MetS and its components, should pay more attention to the type and percentage of macronutrients in this diet.

In our study, LCD decreased the risk of MetS and some of its components including low serum HDL-C, elevated blood pressure, and enlarged waist circumference. The beneficial effects of the low carbohydrate diet on MetS may partially turn to its positive influence on improving endothelial function [33], inflammatory cytokines [34] and adipocytokines [35]. Long-term inflammation is a significant risk factor for metabolic syndrome [36]. On the other hand, low carbohydrate diet was found to significantly improve the inflammatory state [37]; so it's not surprising that a LCD can reduce the risk of metabolic syndrome.

This study has several strengths. Compared to earlier studies conducted in Iran, our study has a larger sample size. This large sample size would be a better representative of the population and therefore, provide more accurate results. Considering a wide range of potential confounders in statistical analyses is another strength of the present study. However, some limitations should be taken into account while interpreting our results. The cross-sectional design of the study does not allow us to confer casual relationships between LCD and MetS. Despite using validated questionnaires for assessment of the exposure and outcome, some degree of misclassification of exposure and outcome is unavoidable. Finally, in the absence of a comprehensive national food composition table, potential inaccuracies in estimating participants' nutrient intake might have arisen; nevertheless, these potential errors did not appear to significantly impact the classification of participants based on their nutrient intake levels.

Conclusion

In conclusion, our findings demonstrated a significant inverse association between LCD and risk of MetS among Iranian adults. Additionally, we found that adherence to LCD significantly reduced the risk of low serum HDL-C, enlarged waist circumference, and elevated blood pressure.

Abbreviations

AHA/NHLBI	American Heart Association/National Heart, Lung and Blood Institute
BMI	Body Mass Index
CVD	Cardiovascular Disease
FBG	Fasting Blood Glucose
FFQ	Food Frequency Questionnaire
HDL-C	High Density Lipoprotein Cholesterol
LCD	Low Carbohydrate Diet
MASHAD	Mashhad Stroke and Heart Atherosclerosis Disorder
MetS	Metabolic Syndrome
MUMS	Mashhad University of Medical Sciences
PAL	Physical Activity Level
T2DM	Type 2 Diabetes Mellitus
TGs	Triglycerides

WC Waist Circumference

Acknowledgements
We thank all participants of the MASHAD study.

Author contributions
S.S., G.K., M.G., S.RY., M.MB., A.G., A.Z., GA.F. and M.GM. contributed to the conception, design, data collection, statistical analyses, data interpretation, manuscript drafting, approval of the final version of the manuscript. M.GM. supervised the study.

Funding
This project was financially supported by the Mashhad University of Medical Sciences, Mashhad, Iran.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The study protocol received ethical approval from the Ethics Committee of Mashhad University of Medical Sciences (MUMS), Mashhad, Iran (Ethics code: IR.MUMS.REC.1386.250). All participants were fully informed about the study and provided written consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 16 April 2024 / Accepted: 12 February 2025
Published online: 10 March 2025

References

1. Grundy SM, Hansen B, Smith SC Jr, Cleeman JI, Kahn RA, Participants C. Clinical management of metabolic syndrome: report of the American Heart Association/National Heart, Lung, and Blood Institute/American Diabetes Association conference on scientific issues related to management. Circulation. 2004; 109(4):551-6.
2. Reaven GM, Banting Lecture. 1988. Role of insulin resistance in human disease. 1988. Nutrition (Burbank, Los Angeles County, Calif). 1997; 13(1):65– 6.
3. Noubiap JJ, Nansseu JR, Lontchi-Yimagou E, Nkeck JR, Nyaga UF, Ngouo AT, et al. Geographic distribution of metabolic syndrome and its components in the general adult population: a meta-analysis of global data from 28 million individuals. Diabetes Res Clin Pract. 2022;188:109924.
4. Farmanfarma KK, Kaykhaei MA, Adineh HA, Mohammadi M, Dabiri S, Ansari-Moghaddam A. Prevalence of metabolic syndrome in Iran: a meta-analysis of 69 studies. Diabetes Metabolic Syndrome: Clin Res Reviews. 2019;13(1):792–9.
5. Zimmet PZ, Magliano DJ, Herman WH, Shaw JE. Diabetes: a 21st century challenge. Lancet Diabetes Endocrinol. 2014;2(1):56–64.
6. Moore JX, Chaudhary N, Akinyemiju T. Peer reviewed: metabolic syndrome prevalence by race/ethnicity and sex in the United States, National Health and Nutrition Examination Survey, 1988–2012. Prev Chronic Dis. 2017; 14.
7. Zieve FJ. The metabolic syndrome: diagnosis and treatment. Clin Cornerstone. 2004;6(Suppl 3):S5–13.
8. Last AR, Wilson SF. Low-carbohydrate diets. Am Fam Physician. 2006;73(11):1942–8.
9. Wylie-Rosett J, Aebersold K, Conlon B, Isasi CR, Ostrovsky NW. Health effects of low-carbohydrate diets: where should new research go? Curr Diab Rep. 2013;13(2):271–8.
10. Sangsefidi ZS, Lorzadeh E, Nadjarzadeh A, Mirzaei M, Hosseinzadeh M. The association between low-carbohydrate diet score and metabolic syndrome among Iranian adults. Public Health Nutr. 2021;24(18):6299–308.
11. Mirmiran P, Asghari G, Farhadnejad H, Eslamian G, Hosseini-Esfahani F, Azizi F. Low carbohydrate diet is associated with reduced risk of metabolic syndrome in tehranian adults. Int J Food Sci Nutr. 2017;68(3):358–65.
12. Askarpour M, Ramezan M, Jafari F, Nouri M, Fattahi MR, Safarpour AR, et al. The association between low carbohydrate diet and odds of metabolic syndrome in adults: a cross-sectional study. Clin Nutr ESPEN. 2023;55:238–43.
13. Ha K, Joung H, Song Y. Low-carbohydrate diet and the risk of metabolic syndrome in Korean adults. Nutr Metab Cardiovasc Dis. 2018;28(11):1122–32.
14. Eslamian G, Mirmiran P, Asghari G, Hosseini-Esfahani F, Youzbashian E, Azizi F. Low carbohydrate diet score does not predict metabolic syndrome in children and adolescents: Tehran lipid and glucose study. Arch Iran Med. 2014;17(6):0.
15. Willems AE, Sura–de Jong M, van Beek AP, Nederhof E, van Dijk G. Effects of macronutrient intake in obesity: a meta-analysis of low-carbohydrate and low-fat diets on markers of the metabolic syndrome. Nutr Rev. 2021;79(4):429–44.
16. Kimiagar S, Ghaffarpour M, Houshiar Rad A, Hormozdyari H, Zellipour L. Food consumption pattern in the Islamic Republic of Iran and its relation to coronary heart disease. EMHJ-Eastern Mediterranean Health Journal, 4 (3), 539–547, 1998. 1998.
17. Ghayour-Mobarhan M, Moohebati M, Esmaily H, Ebrahimi M, Parizadeh SMR, Heidari-Bakavoli AR, et al. Mashhad stroke and heart atherosclerotic disorder (MASHAD) study: design, baseline characteristics and 10-year cardiovascular risk estimation. Int J Public Health. 2015;60:561–72.
18. Ahmadnezhad M, Asadi Z, Miri HH, Ebrahimi-Mamaghani M, Ghayour-Mobarhan M, Ferns GA. Validation of a short semi-quantitative food frequency questionnaire for adults: a pilot study. J Nutritional Sci Dietetics. 2017:49–55.
19. Grundy SM, Brewer HB Jr, Cleeman JI, Smith SC Jr, Lenfant C. Definition of metabolic syndrome: report of the National Heart, Lung, and Blood Institute/American Heart Association conference on scientific issues related to definition. Circulation. 2004; 109(3):433-8.
20. Delavari A, Forouzanfar MH, Alikhani S, Sharifian A, Kelishadi R. First nationwide study of the prevalence of the metabolic syndrome and optimal cutoff points of waist circumference in the Middle East: the national survey of risk factors for noncommunicable diseases of Iran. Diabetes Care. 2009;32(6):1092–7.
21. Asadi Z, Yaghooti-Khorasani M, Ghazizadeh H, Sadabadi F, Mosa-Farkhany E, Darroudi S, et al. Association between dietary inflammatory index and risk of cardiovascular disease in the Mashhad stroke and heart atherosclerotic disorder study population. IUBMB Life. 2020;72(4):706–15.
22. Bahari H, Seifi N, Foroumandi E, Kourepaz F, Shahabi HE, Ervin K, et al. Dietary acid load, depression, and anxiety: results of a population-based study. BMC Psychiatry. 2023;23(1):679.
23. Hajian-Tilaki K. Metabolic syndrome and its associated risk factors in Iranian adults: a systematic review. Caspian J Intern Med. 2015;6(2):51.
24. Hosseinpour-Niazi S, Mirmiran P, Hosseinpanah F, Fallah-Ghohroudy A, Azizi F. Association of marital status and marital transition with metabolic syndrome: tehran lipid and glucose study. Int J Endocrinol Metabolism. 2014; 12(4).
25. Shirani F, Esmaillzadeh A, Keshteli AH, Adibi P, Azadbakht L. Low-carbohydrate-diet score and metabolic syndrome: an epidemiologic study among Iranian women. Nutrition. 2015;31(9):1124–30.
26. Ismael SA. Effects of low carbohydrate diet compared to low fat diet on reversing the metabolic syndrome, using NCEP ATP III criteria: a randomized clinical trial. BMC Nutr. 2021;7(1):62.
27. Freire RD, Cardoso MA, Gimeno SG, Ferreira SR, Group J-BDS. Dietary fat is associated with metabolic syndrome in Japanese brazilians. Diabetes Care. 2005;28(7):1779–85.
28. Santos FL, Esteves SS, da Costa Pereira A, Yancy WS Jr, Nunes JP. Systematic review and meta-analysis of clinical trials of the effects of low carbohydrate diets on cardiovascular risk factors. Obes Rev. 2012;13(11):1048–66.
29. Dong T, Guo M, Zhang P, Sun G, Chen B. The effects of low-carbohydrate diets on cardiovascular risk factors: a meta-analysis. PLoS ONE. 2020;15(1):e0225348.
30. Nordmann AJ, Nordmann A, Briel M, Keller U, Yancy WS, Brehm BJ, et al. Effects of low-carbohydrate vs low-fat diets on weight loss and cardiovascular risk factors: a meta-analysis of randomized controlled trials. Arch Intern Med. 2006;166(3):285–93.
31. Jamshidi A, Farjam M, Ekramzadeh M. Evaluating type and amount of dietary protein in relation to metabolic syndrome among Iranian adults: cross-sectional analysis of Fasa Persian cohort study. 2022; 14(1):42.
32. Clifton P. Metabolic syndrome—role of dietary fat type and quantity. Nutrients. 2019;11(7):1438.
33. Shai I, Spence JD, Schwarzfuchs D, Henkin Y, Parraga G, Rudich A, et al. Dietary intervention to reverse carotid atherosclerosis. Circulation. 2010;121(10):1200–8.

34. Bladbjerg E-M, Larsen TM, Due A, Stender S, Astrup A, Jespersen J. Effects on markers of inflammation and endothelial cell function of three ad libitum diets differing in type and amount of fat and carbohydrate: a 6-month randomised study in obese individuals. Br J Nutr. 2011;106(1):123–9.
35. Wycherley TP, Brinkworth G, Keogh J, Noakes M, Buckley J, Clifton P. Long-term effects of weight loss with a very low carbohydrate and low fat diet on vascular function in overweight and obese patients. J Intern Med. 2010;267(5):452–61.
36. Jonasson L, Guldbrand H, Lundberg AK, Nystrom FH. Advice to follow a low-carbohydrate diet has a favourable impact on low-grade inflammation in type 2 diabetes compared with advice to follow a low-fat diet. Ann Med. 2014;46(3):182–7.
37. Esposito K, Giugliano D. The metabolic syndrome and inflammation: association or causation? In. Volume 14. Elsevier; 2004.

Publisher's note