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Magnesium Status and Dietary Patterns Associated with Glycemic Control in Individuals with Type 2 Diabetes Mellitus

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Abstract

Hypomagnesemia and unhealthy eating patterns are associated with poor glycemic control in individuals with type 2 diabetes mellitus (T2DM). This study aimed to associate magnesium status and dietary patterns with glycemic control in T2DM individuals. This cross-sectional study included 147 individuals with T2DM, aged between 19 and 59 years, of both sexes, residents in Sergipe/Brazil. The BMI, waist circumference, %body fat, plasma magnesium, serum glucose, insulin, %HbA1c, triacylglycerol, total cholesterol, LDL-c, and HDL-c were analyzed. Eating patterns were identified using a 24-h recall method. Logistic regression models were used to verify the association of magnesium status and dietary patterns with markers of glycemic control by adjusting for sex, age, time of T2DM diagnosis, and BMI. A P value < 0.05 was considered significant. Magnesium deficiency increased the chance of elevated %HbA1c by 5.893-fold ($P = 0.041$). Three main dietary patterns were identified: mixed (MDP), unhealthy (UDP), and healthy (HDP). UDP also increased the chance of elevated %HbA1c levels ($P = 0.034$). T2DM individuals' who presented magnesium deficiency had a higher chance of elevated %HbA1c levels (8.312-fold) and those in the lowest quartile (Q) of the UDP (Q1: $P = 0.007$; Q2: $P = 0.043$) had a lower chance of elevated %HbA1c levels. However, the lower quartiles of the HDP were associated with a greater chance of alterations in the %HbA1c level (Q1: $P = 0.050$; Q2: $P = 0.044$). No association was observed between MDP and the variables studied. Magnesium deficiency and UDP were associated with a higher chance of inadequate glycemic control in T2DM individuals.

Keywords Type 2 diabetes mellitus · Dietary pattern · Magnesium · Metabolic control

Introduction

In recent decades, the association of dietary factors with the risk of developing diabetes and increased inflammation, including high consumption of saturated fatty acids, sugary drinks, and starchy foods, combined with low consumption

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of fruits, vegetables, and whole grains, has been widely investigated [1]. Dietary patterns represent the totality of foods and beverages consumed by a person over a period of time; therefore, they are considered the most realistic measure of food consumption [2].

In general, nutritional studies investigating the relationship of nutrients or foods with chronic diseases, including type 2 diabetes mellitus (T2DM), encounter limitations as the human diet are complex [3]. Moreover, each food is not consumed individually, and nutrients operate in a synergistic or inhibitory manner, making it difficult to detect these possible associations [4]. This fact justifies the global consideration of the use of dietary patterns as an alternative to overcome these limitations by analyzing the effects of multiple dietary factors on individuals' health [5].

On the contrary, evidence from cohort and prospective studies and clinical trials have shown the importance of nutrients for the prevention and control of T2DM [6, 7]. Among the various nutrients, magnesium is an essential mineral for glucose homeostasis by acting directly on the activity of glucose transporter protein 4 and the regulation of glucose entry into the cell [7]. Previous studies have observed the occurrence of magnesium deficiency in individuals with T2DM and reported its inverse relationship with metabolic control [8].

In this sense, the synergistic effects of dietary patterns must be evaluated, taking into account the nutrients, quantity, and quality of food consumed. Considering that the choice of food is of great importance for the relationship between good glycemic control and the complications associated with the disease, we hypothesized that magnesium deficiency and adherence to unhealthy dietary patterns are associated with poor glycemic control in T2DM. Thus, this study aimed to evaluate the magnesium status and dietary patterns and its relationship with glycemic control among individuals with T2DM.

Methods

Study Population

This cross-sectional study evaluated 147 individuals aged 19 to 59 years, of both sexes, with diagnostic of T2DM, and who attended primary health care in the state of Sergipe, Brazil. Participants were enrolled in the study between May 2017 and December 2019. From lists with the names and contacts of individuals with T2DM made available by health agents in primary care, the researchers contacted the individuals, and thus the exclusion criteria were screened. After this first contact, an appointment was made with the individuals on an agreed date to collect blood and other data.

Individuals who had smoking habits, consumed alcoholic beverages regularly, used vitamin-mineral supplements, were pregnant, or had other chronic diseases such as cancer, thyroid problems, arthritis, or renal diseases were excluded from the study.

This study was approved by the Ethics Committee on Human Research of the Federal University on Sergipe (opinion no. 3.012.056) and conducted according to Helsinki Declaration. All participants provided a written informed consent.

Data Collection

A questionnaire was administered to obtain the data on socio-economic characteristics, presence of diseases, use of medications, and time of T2DM diagnosis, among others. Anthropometric and body composition measurements were obtained, and the biochemical markers of glycemic and lipid control, and concentration of plasma magnesium were determined. The individuals' food intake was evaluated to identify their dietary patterns and associate with the outcome variables.

Anthropometric and Body Composition Assessment

Weight and height were measured to obtain the BMI (kg/m^2), and the results were classified according to the cutoff values established by the World Health Organization (WHO) [9]. Waist circumference (WC) was measured using an inelastic tape at the midpoint between the lower rib margin and the iliac crest, and the results were classified according to the WHO criteria [10].

The fat percentage was evaluated using a tetrapolar bioelectrical impedance scale (Biodynamics®, model 310, WA, USA). The individuals were previously instructed not to perform physical exercises and to avoid consuming coffee, tea, soda, alcoholic beverages, or chocolate a day before the test. Additionally, they were asked to empty their bladder prior to the start of the evaluation. The fat percentage was classified according to the values proposed by Lohman et al. [11].

Blood Collection

Blood samples (15 mL) were collected from the participants (after fasting for 10 h) using sterile, disposable syringes and were transferred to ethylenediaminetetraacetic acid anticoagulant tubes to determine the glycated hemoglobin percentage (%HbA1c) and to dry tubes to obtain the serum that will be used for analyzing the markers of glycemic and lipid profiles. The serum was separated from the whole blood by centrifugation at 3000 rpm for 15 min at 4 °C. Then, they were stored at – 80 °C until analysis.

Analysis of Plasma Magnesium Concentration

Initially, the samples were digested in a thermal block for 2 h at 150 °C. The procedure was performed using plasma (0.5 mL), pure nitric acid (2 mL), and nanopure water (3 mL). Then, the digested samples were diluted in nanopure water to a final volume of 15 mL, and the magnesium concentration was analyzed using the optical emission spectrometry method with inductively coupled plasma. The external calibration curves were prepared using SpecSols multielement standards at a concentration of 100 mg/L [12]. A plasma magnesium value of less than 0.75 nmol/L indicated magnesium deficiency, while that between 0.75 and 1.05 nmol/L was considered normal [13].

All reagents used were prepared with high-pressure water (resistivity: 18.2 MO cm) and obtained using a Milli-Q purification system (Millipore, USA); the material used (glassware, plastics, tips, tubes, etc.) were demineralized in a 20% nitric acid bath for at least 12 h and rinsed 10 times with nanopure water.

Analysis of Markers of Glycemic and Lipid Control

The fasting serum glucose concentration was determined using the colorimetric method, while the %HbA1c level was measured by an enzymatic method using commercial kits (Labtest, Lagoa Santa, Minas Gerais, Brazil). To evaluate the lipid profile, the serum concentrations of total cholesterol (TC), high-density lipoprotein cholesterol (HDL-c), and triacylglycerol (TAG) were determined using colorimetric methods. The low-density lipoprotein cholesterol (LDL-c) concentration was calculated using the Friedwald equation [14]. The results were classified according to the Brazilian Society of Diabetes [15] and the Brazilian Society of Cardiology [16].

Assessment of Food Intake

Food intake was assessed using three 24-h food recall (R24h) forms, which were administered on alternate days, with one day being on the weekend. The first R24h was performed in person on the day of blood collection, while the other sessions were conducted over the phone, according to the Multiple Pass Method [17].

The data obtained were analyzed using the NutWin software. This software contains data from the Brazilian Table of Food Composition, the United States Department of Agriculture table of food composition consumed in Brazil, and data from food labels provided by manufacturers. The inadequacy of the usual dietary intake of macronutrients and magnesium, calcium, zinc, and potassium were evaluated according to the acceptable macronutrient distribution ranges (AMDR) [18] and estimated average requirement and adequate intake for potassium [19], respectively.

Statistical Analyses

A descriptive analysis of the data was performed (frequency [n(%)] and mean [standard deviation—SD]). The Kolmogorov–Smirnov normality test was applied. Pearson's or Spearman's correlation test was performed according to the data distribution.

The usual dietary intake was assessed using the multiple source method. Then, Willet's residual method was used to adjust the macronutrients and micronutrients by daily energy intake [20]. From the R24h data, the amounts of each food obtained through household measure were converted to grams or milliliters in the NutWin Software. The foods were listed and grouped in an Excel spreadsheet, taking into account the nutritional composition, to reduce the number of food variables, since the R24h allows an unlimited number of items to be listed.

The foods were grouped to obtain the mean absolute intake in grams/day for each food group. Thirty food groups were formed according to their similarity in nutritional composition: "fruits"; "vegetables"; "roots and tubers"; "legumes"; "beans"; "rice"; "pasta"; "poultry"; "pork"; "red meats"; "fish and seafood"; "eggs"; "sausages"; "dairy products and porridges"; "sweeteners"; "sugar"; "natural beverages"; "processed beverages"; "coffees and infusions"; "alcoholic beverages"; "whole grains and flours"; "breads, toasts, and cookies"; "breads, toast and cookies of whole grain"; "industrialized"; "sweets"; "oils and oilseeds"; "local traditional foods"; "soups and broths"; "snacks and fried foods"; and "fats."

A priori, factor analysis was performed using a uniform sample to verify the distribution of the variables in a loading plot, contrasting the values obtained with those expected for a normal distribution. Bartlett's test of sphericity and the Kaiser Meyer-Olkin coefficient (KMO) test were performed, and the cutoff values of $P \leq 0.05$ and KMO ≥ 0.50, respectively [21, 22], indicated a satisfactory confidence level for the factor analysis.

Subsequently, principal component analysis was performed, starting with the extraction of the factors. The number of factors was selected using the Kaiser criterion (eigenvalues: > 1.0) and the scree plot analysis, through the eigenvalues plot, which explains the total variance associated with each factor [23, 24].

The factor loadings, which measure the correlations between factors, were analyzed using the varimax method of orthogonal rotation [25]. The factor loadings were either ≥ 0.25 (indicating a direct correlation with the pattern) or ≤ -0.25 (indicating an inverse correlation with the pattern) [25]. The loading plots helped determine the factor loadings based on the location of the variables in the coordinate system. The dietary patterns were classified based on the foods that are included in each pattern.

Additionally, logistic regression models were tested to identify whether the identified dietary patterns and magnesium status were predictive of altered %HbA1c levels. Factorial scores were distributed in quartiles to assess whether higher adherence to each pattern associated with magnesium status predicted the changes in %HbA1c levels. These models were adjusted by age, sex, BMI, and time of diagnosis. A *P* value of less than 5% was considered significant. Model fit was verified using the Hosmer and Lemeshow test. Additionally, the multicollinearity analysis was checked using the variance inflation factor (VIF)/tolerance, being that all models presented VIFs below 2, and the tolerance measures were ≥ 0.7 (reference for VIF < 5 and tolerance > 0.2). Statistical analyses were performed using the Statistical Package for Social Science software (version 27.0).

Results

Characteristics of the Study Population

A total of 147 individuals with T2DM were evaluated, and 68% ($n = 100$) of them were women. The mean age and time of disease diagnosis were 48.71 (SD: 7.84) years and 6.81 (SD: 6.18) years, respectively. Most individuals had completed elementary school (59.6%) and did not practice physical activity (54.4%). The socioeconomic, lifestyle, anthropometric, clinical, and metabolic control characteristics of individuals with T2DM are shown in Table 1.

The individuals evaluated had a mean BMI of 30.27 (SD: 6.14) kg/m^2, and majority of them were overweight (40.1%) and obese (42.9%) (Table 1). Moreover, the individuals presented a mean WC of 99.83 (SD: 13.05) cm; approximately 9.50% and 54.40% of the women presented increased and substantially increased risk of cardiovascular diseases, respectively, while 11.60% and 12.20% of men had increased and substantially increased risk of cardiovascular diseases, respectively. Additionally, 61.2% of the participants had a risk of developing diseases associated with obesity, according to their body fat percentage.

Regarding glycemic control, 83.67% and 60.96% of the individuals evaluated presented poor glycemic control based on their fasting blood glucose values and %HbA1c levels according to Brazilian Society of Diabetes [15], respectively. Additionally, 44.90% of the individuals presented high TAG levels, 54.42% presented HDL-c levels below the reference values, and 52.38% and 70.75% presented total cholesterol and LDL-c levels above the values recommended by the Brazilian Society of Cardiology [16], respectively.

Table 1 Socioeconomic, lifestyle, clinical, body composition, and biochemical characteristics of individuals with T2DM

Variables	Mean (SD) or *n* (%)
Age (years)	48.71 (7.84)
Sex	
Female [*n* (%)]	100 (68)
Male [*n* (%)]	47 (32)
Time of diagnosis (years)	6.81 (6.18)
Insulin use [*n* (%)]	28 (19.1)
Education level	
High school or below [*n* (%)]	128 (87.7)
College or above [*n* (%)]	11 (7.5)
No schooling [*n* (%)]	7 (4.8)
Drinking [*n* (%)]	15 (10.2)
Ex-smoker [*n* (%)]	31 (21.1)
Practice of physical activity [*n* (%)]	67 (45.6)
BMI (kg/m^2)	30.27 (6.14)
BMI classification	
Malnutrition [*n* (%)]	3 (2)
Normal-weight [*n* (%)]	22 (15)
Overweight [*n* (%)]	59 (40.1)
Obesity degree 1 [*n* (%)]	35 (23.8)
Obesity degree 2 [*n* (%)]	17 (11.6)
Obesity degree 3 [*n* (%)]	11 (7.5)
WC (cm)	99.83 (13.05)
Fat mass (kg)	29.17 (13.48)
Fat mass (%)	36.81 (10.55)
Lean mass (kg)	48.40 (9.44)
Lean mass (%)	61.11 (12.74)
Plasma magnesium (mmol/L)	0.572 (0.145)
HbA1c (%)	8.22 (2.30)
Fasting serum glucose (mg/dL)	180.49 (84.22)
Serum insulin (μU/mL)	12.54 (11.96)
TAG (mg/dL)	168.06 (110.97)

Results are presented as absolute (*n*) and relative (%) frequency for categorical data and mean and standard deviation (SD) for continuous data. *BMI* body mass index, *WC* waist circumference, Hb_{A1c} glycated hemoglobin, *TAG* triacylglycerols. Reference values: fasting glucose: < 100 mg/dL and %HbA1c: < 7% [15]; triglycerides: < 150 mg/dL (desirable); plasma magnesium > 0.75 nmol/L (adequate) [13]

Results of the evaluation of magnesium levels in individuals with T2DM showed that 92.5% of them had magnesium deficiency, as evidenced by the mean concentration of plasma magnesium presented in Table 1.

In the evaluation of the usual dietary intake of macronutrients, the mean percentage of energy distribution for carbohydrates, lipids, and proteins was within the AMDR recommended by the Institute of Medicine [18] (Supplementary Table 1). The dietary intakes of magnesium, zinc, calcium, and potassium were deficient in most individuals assessed, as evidenced by their mean daily intake (Supplementary

Table 1) and the prevalence of inadequacy in these nutrients (Supplementary Fig. 1). The prevalence rates of inadequate magnesium intake in the population studied were 87.2% in men and 82% in women. Moreover, the prevalence rates of inadequate zinc intake were 93.6% in men and 87% in women. The prevalence of inadequate calcium intake was 93.2%, while that of inadequate potassium intake was 94.6%.

When correlating micronutrient intake with glycemic control markers, potassium was inversely related to glucose ($r = -0.165$, $P = 0.045$) and %HbA1c levels ($r = -0.199$, $P = 0.016$). Magnesium intake was inversely correlated with the %HbA1c levels ($r = -0.195$, $P = 0.019$). The other minerals did not correlate significantly with glycemic variables (data not shown).

Food Pattern

The observed KMO value was 0.58, indicating that the sample was considered adequate for factor analysis. Through this analysis, based on Kaiser's criteria and the scree plot, 12 components were identified (Fig. 1), and the first three factors were chosen, which were responsible for the sample variability of 28.70%.

Table 2 shows the factorial loadings of each food group obtained after varimax rotation. The first factor (named mixed) explained 13.83% of the total variance of the sample and was characterized by the consumption of beans; rice; pork; dairy products and porridge; sweeteners; natural beverages; processed beverages; coffee and infusions; bread, toast, and cookies; local habit foods; and fats. The second factor (named unhealthy) showed a variance of 7.90%. This pattern was characterized by the consumption of red meat, eggs, local habit foods, and salty and fried foods. The third factor (named healthy) showed a variance of 6.96% and was characterized by the consumption of fruits, vegetables, roots and tubers, rice, fish and seafood, eggs, coffees and infusions, and local habit foods.

When correlating the factor loadings of dietary patterns with micronutrient intake, magnesium, calcium, and potassium were found to be inversely related to unhealthy dietary pattern ($r = -0.477$, $P < 0.001$; $r = -0.488$, $P < 0.001$; and $r = -0.586$, $P < 0.001$, respectively) and directly related to healthy dietary pattern ($r = 0.265$, $P < 0.001$; $r = 0.372$, $P < 0.001$; and $r = 0.335$, $P < 0.001$, respectively). Zinc was correlated only with dietary pattern mixed ($r = 0.312$, $P < 0.001$) (data not shown in tables).

As for the glycemic control variables, %HbA1c was directly correlated with the factor loadings of food patterns mixed and unhealthy ($r = 0.194$, $P = 0.019$; $r = 0.181$, $P = 0.029$, respectively) and inversely correlated with pattern healthy ($r = -0.166$, $P = 0.046$). Similarly, glucose concentrations were directly correlated with dietary pattern mixed ($r = 0.202$, $P = 0.014$) and inversely with pattern healthy ($r = -0.166$, $P = 0.044$), while pattern unhealthy showed no significant correlation ($r = 0.157$, $P = 0.057$) (data not shown in tables).

When assessing the association of dietary patterns and plasma magnesium with %HbA1c, magnesium deficiency and dietary pattern unhealthy increased the odds of elevating the %HbA1c levels by 5.893-fold ($P = 0.041$) and 1.550-fold ($P = 0.034$), respectively, after adjusting for sex, age, time of T2DM diagnosis, and BMI (Table 3).

Corroborating the above results, we distributed the factorial scores of each dietary pattern by quartile and tested the binary logistic regression models considering the same adjustment variables as in the previous table (Table 4). In

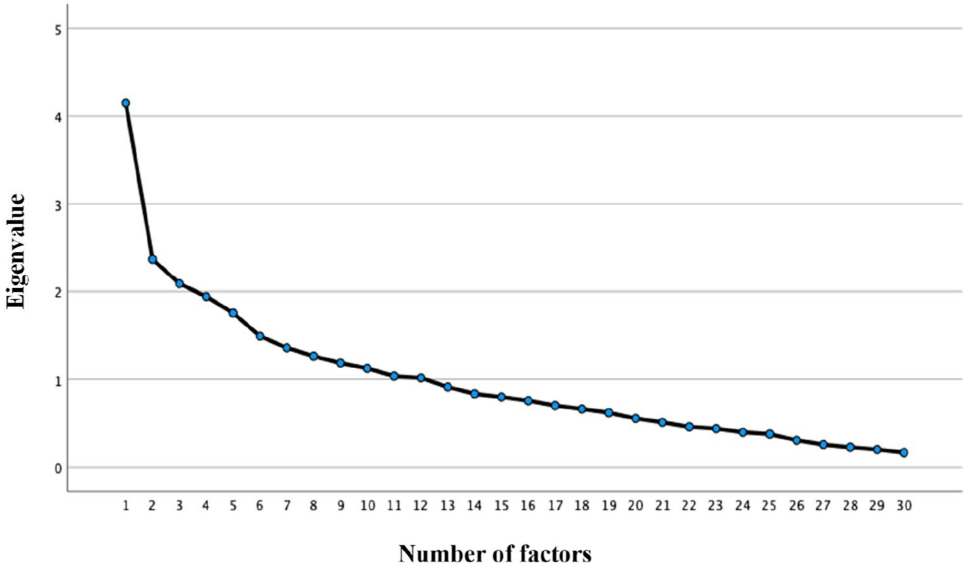

Fig. 1 Scree plot of the eigenvalues for each component in the factor extraction from the 24-h dietary recall

Table 2 Factorial loadings obtained through *Varimax* rotation to obtain the dietary patterns of individuals with T2DM

Food categories	Mixed dietary pattern	Unhealthy dietary pattern	Healthy dietary pattern
Fruit	−0.049	**−0.485**	**0.276**
Vegetables	0.084	−0.190	**0.649**
Roots and tubers	−0.032	−0.115	**0.415**
Legumes	−0.014	0.028	−0.116
Beans	**0.674**	0.079	0.043
Rice	**0.540**	0.229	**0.400**
Pasta	0.046	0.136	**−0.329**
Poultry	0.054	0.010	0.215
Pork	**0.596**	−0.105	−0.083
Red meats	0.128	**0.339**	**−0.254**
Fish and seafood	0.089	0.147	**0.686**
Egg	−0.074	**0.338**	**0.368**
Sausages	0.183	0.203	**−0.252**
Dairy products and porridge	**0.329**	**−0.577**	0.028
Sweeteners	**0.718**	−0.029	−0.047
Sugar	0.066	0.024	−0.085
Natural beverages	**0.413**	−0.025	**−0.298**
Industrialized beverages	**0.502**	0.212	0.092
Coffees and Infusions	**0.747**	0.096	**0.257**
Beverages	0.014	0.243	**−0.261**
Whole grains and flours	0.012	**−0.528**	0.123
Breads, toasts, and cookies	**0.782**	0.141	0.028
Breads, toasts, and cookies of the whole grain	−0.081	**−0.581**	0.122
Industrialized	0.059	0.123	−0.066
Sweets	0.126	−0.228	**−0.251**
Oils and oilseeds	−0.020	0.107	−0.226
Local habit foods	**0.273**	**0.586**	**0.405**
Soups and broths	−0.090	0.013	0.090
Salty and fried food	0.136	**0.419**	0.017
Fats	**0.655**	0.037	−0.035
Explained variance	13.836	7.904	6.961
Cumulative variance	13.836	21.740	28.701

Factorial loadings ≥ 0.25 and ≤ −0.25 are considered significant contributors to the pattern, as highlighted in bold

Table 3 Logistic regression model between %HbA1c (dependent variable) and the variables plasma magnesium, dietary patterns mixed, unhealth, and health (predictor variables) of individuals with T2DM

	%HbA1c*		
Covariables	OR	CI 95%	*p* valor
Magnesium deficiency	5.893	(1.076; 32.259)	0.041
Mixed dietary pattern	1.011	(0.662; 1.543)	0.960
Unhealthy dietary pattern	1.550	(1.034; 1.543)	0.034
Healthy dietary pattern	0.742	(0.500; 1.095)	0.133

Adjustment variables: gender, age, time of diagnosis (years) and body mass index. *Risk classification used %HbA1c > 7% [15]. Plasma magnesium status considered deficient if magnesium value < 0.75 nmol/L [13]. *%HbA1c* glycated hemoglobin percentage, *OR* odds ratio, *CI* confidence interval. *P* < 0.05 considered significant

Table 4 Binary logistic regression model between %HbA1c (dependent variable) and quartiles (Q) of identified dietary patterns of individuals with T2DM

Covariables	%HbA1c*		
	OR (EXP)	CI95%	*p* valor
Model 1			
Magnesium deficiency	5.658	(1.082; 29.577)	0.040
Mixed dietary pattern (quartiles)			
Q1	0.617	(0.212; 1.793)	0.375
Q2	0.825	(0.283; 2.409)	0.825
Q3	1.040	(0.353; 3.066)	0.944
Q4	Ref		
Model 2			
Magnesium deficiency	8.312	(1.545; 44.717)	0.014
Unhealthy dietary pattern (quartiles)			
Q1	0.207	(0.066; 0.652)	0.007
Q2	0.295	(0.090; 0.964)	0.043
Q3	0.593	(0.185; 1.907)	0.381
Q4	Ref		
Model 3			
Magnesium deficiency	5.022	(0.955; 26.402)	0.570
Healthy dietary pattern (quartiles)			
Q1	2.930	(1.001; 8.578)	0.050
Q2	2.556	(1.023; 6.385)	0.044
Q3	1.494	(0.389; 5.741)	0.559
Q4	Ref		

Adjustment variables: gender, age, time of diagnosis (years) and body mass index. *Risk classification used %HbA1c > 7% [15]. Magnesium status considered deficient if mg value < 0.75 nmol/L nmol/L [13]. *Q* quartile, *%HbA1c* glycated hemoglobin percentage, *OR* odds ratio, *CI* confidence interval. *P* < 0.05 considered significant

model 1, only magnesium deficiency was predictive of the changes in %HbA1c level (OR = 5.658). In model 2, magnesium deficiency was also predictive of the increase in %HbA1c level, and lower adherence to the unhealthy dietary pattern, which is characterized by the consumption of red meat, eggs, local and salty foods, and fried foods, reduced the chances of elevating the %HbA1c, as observed in Q1 and Q2, respectively (*P* = 0.007 and *P* = 0.043). By contrast, the lowest quartiles of healthy dietary pattern, which represents lower adherence to this pattern, were associated with the highest odds of increasing the %HbA1c level (Q1: *P* = 0.050; Q2: *P* = 0.044). Other models were tested to verify the association between eating patterns and glycemic and lipid variables, but the results were not significant.

Discussion

The high prevalence of plasma magnesium deficiency in the present study sample was associated with an increased %HbA1c level. In parallel, three main eating patterns were identified and represent the dietary habits of individuals with T2DM, of which unhealthy eating pattern, characterized by the consumption of red meat, eggs, local foods, and salty and fried foods along with magnesium deficiency, was associated with the highest chance of increasing the %HbA1c level. Furthermore, lower adherence to the healthy dietary pattern, characterized by consumption of vegetables, roots, tubers, rice, fish and seafood, eggs, and local foods, was also associated with poorer glycemic control.

Serum magnesium concentrations are inversely associated with glycemic markers (glucose, fasting insulin, and %HbA1c) [26] and BMI [27]. Other studies have observed negative associations between serum magnesium concentration and insulin resistance, and positively with insulin sensitivity [26, 28]. On the contrary, poor glycemic control reduces the serum concentrations of this nutrient by affecting the tubular reabsorption of magnesium [26, 29]. Studies relating both dietary patterns and micronutrient-related nutritional status with glycemic markers in the T2DM population are limited, especially with nutrients that are involved in metabolic control. In addition, these micronutrients are also components of the foods that comprise dietary patterns known to be beneficial for reducing the risk of metabolic diseases, such as the DASH dietary pattern, which promotes the reduction of blood pressure by encouraging the consumption of foods low in saturated fat, total fat, cholesterol, and sodium and high levels of potassium, calcium, magnesium, fiber, and protein [30].

Dietary patterns have been studied to promote a greater understanding of the relationship between diet and diseases, especially chronic noncommunicable diseases [31], as their effects are related to the interaction between the foods that comprised each pattern. Thus, different dietary patterns can positively or negatively affect the metabolic control of individuals with T2DM [32].

Similar to the findings of the present study, Dekker et al. [33] found some associations between the "meats and snacks" eating patterns with increased %HbA1c and fasting blood glucose levels. Another study showed that %HbA1c level was also elevated among individuals with T2DM who had a higher intake of cereals, vegetables, and meats compared with those with moderate intake of cereals and meats, high intake of vegetables, low intake of cereals, and moderate intake of vegetables and meats [34].

The increase in %HbA1c level associated with dietary patterns that involved the consumption of meat can be explained by the high amounts of saturated fat that is directly associated with hyperinsulinemia and the increased level of insulin resistance [35, 36]. Additionally, when this type of food is cooked, the formation of advanced glycation end products that can increase the production of pro-inflammatory cytokines, such as tumor necrosis factor-alpha (TNF-α) and interleukins, which are related to increased complications of T2DM [37, 38].

Unhealthy dietary patterns are also associated with increased levels of circulating lipids, as observed by Buscemi et al. [39] who reported that an unhealthy eating pattern (high consumption of soft drinks, fried foods, seed oils, cured meats, butter, red meats, and sweets) was associated with a higher TAG/HDL-c ratio than the other patterns evaluated (the Mediterranean dietary pattern and intermediate dietary pattern). In the present study, no associations were observed between the identified food patterns and the variables of lipid control in individuals with T2DM.

The consumption of foods that make up the dietary pattern recommended by "MyPlate" for individuals with T2DM in the Arab Emirates was associated with lower %HbA1c level; the consumption of fresh fruits promoted glycemic control, while the consumption of soft drinks and fast foods at least once a week increased the risk of poor metabolic control. That study also found that fruit juice intake more than once a day was predictive of poor glycemic control [40].

The lower adherence to the healthy dietary pattern was also associated with higher odds of increasing the %HbA1c level to > 7%. In a study by Sarmento et al. [41], the healthy eating patterns (characterized by consumption of fruits, vegetables, whole-wheat cereals, dairy products, low-fat meats, and fish) were associated with a reduction in fasting plasma glucose, %HbA1c, and LDL-c cholesterol levels. In another study conducted in Brazil, a similar pattern called "healthy pattern" (characterized by consumption of natural fruits and juices, olive oil and oilseeds, roots, tubers, and vegetables) showed no correlation with serum glucose concentrations [22]. However, they observed a negative correlation between traditional Brazilian food patterns (characterized by consumption of rice, beans, and chicken) and serum glucose concentrations.

The composition of foods that characterize the healthy dietary pattern may have favorable effects on glycemic control due to the marked presence of fiber, antioxidant substances, unsaturated fatty acids, and micronutrients such as magnesium, zinc, and potassium [42–44]. These nutrients improve glycemic control by reducing postprandial glycemia [42] and %HbA1c levels [45] as well as by improving insulin resistance [42]. Moreover, these foods act positively on satiety [46]. The T2DM individuals assessed in this study showed a high prevalence of inadequate intake of magnesium, zinc, calcium, and potassium; the %HbA1c levels correlated negatively with the dietary intake of magnesium and potassium, while the serum glucose concentration correlated negatively with the intake of potassium. Previous studies have pointed out that these minerals are associated with better glycemic control; however, they have been studied separately, and individuals with T2DM has less intake of these minerals in most of these studies [47–49]. Brandão-Lima et al. [50] observed that reduced intake of zinc, calcium, magnesium, and phosphorus was associated with a greater chance of increasing the %HbA1c level to > 7% in individuals with T2DM than in those with higher intake of this mineral.

However, the use of R24h to assess the nutrient intake has certain limitations such as the need for the individual's memory to accurately report the foods and portions consumed, and the frequency of underreporting by overweight individuals. However, to reduce the bias, the intra- and inter-individual variabilities and adjustment of micronutrient intake by energy intake were performed. Notably, the strength of this study was the inclusion of results of the plasma magnesium concentration concomitant with the analysis of dietary patterns since this nutrient plays a strong role in insulin action and in promoting glycemic control and few studies have been conducted with this dual approach. It is noteworthy that this approach including micronutrient assessment combined with dietary patterns is not often observed in studies. This suggests new perspectives for evaluating specific dietary patterns that promote better glycemic control, as seen in the Dash dietary pattern that includes micronutrients that favor blood pressure control.

Conclusion

We conclude that the plasma magnesium deficiency and adhesion to a dietary pattern consisting of red meat, eggs, regional foods, salty, and fried foods, considered unhealthy, were associated with poor glycemic control. Moreover, this dietary pattern also was directly related to a lower intake of magnesium, calcium, and potassium due to the composition of the foods that characterize it. Lower adherence to the healthy dietary pattern and the presence of concomitant plasma magnesium deficiency was also associated with poor glycemic control, since the foods that characterize this pattern (fruits; vegetables; roots and tubers; rice; fish and seafood; eggs; coffees and infusions; and local habit foods) present good nutrient density, for rich in micronutrients such as magnesium, and are low in calories, and relate to better diabetes control. These results show that for better glycemic control, it is necessary to adopt eating patterns that contain foods that can interact in a beneficial way, improving the nutritional status of micronutrients, given the high prevalence of inadequate intake of magnesium, zinc, calcium, and potassium, as well as plasma magnesium deficiency.

Therefore, a combined approach that explains such relationships strengthens the understanding of the interactions between the nutrients that make up dietary patterns and the synergy between them. Thus, studies of this nature that aim to understand the interactions between dietary patterns and nutritional status related to micronutrients are important for the development of nutritional strategies aimed at the metabolic control of individuals with T2DM, favoring the reduction of the risk of complications associated with the disease and improvement in the quality of life of this population.

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Declarations

Competing Interests The authors declare no competing interests.

References

1. Luk AO, Lau ES, So WY, Ma RC, Kong AP, Ozakiet R, Chow FC, Chan JC (2014) Prospective study on the incidences of cardiovascular-renal complications in chinese patients with young-onset type 1 and type 2 diabetes. Diabetes Care 37(1):149–157. https://doi.org/10.2337/dc13-1336
2. Martínez MLR, Gómez-Díaz RA, González ALV, González RM, Becerra MCS, Rio SLGD, Cruz M, Wacher-Rodarte NH, Pacheco RAR, Aburto VHB (2020) Association between glycemic control and dietary patterns in patients with type 2 diabetes in a Mexican institute. Nutrition 78:110901. https://doi.org/10.1016/j.nut.2020.110901
3. Frank LK, Kröger J, Schulze MB, Bedu-Addo G, Mockenhaupt FP, Danquah I (2014) Dietary patterns in urban Ghana and risk of type 2 diabetes. Br J Nutr 112(1):89–98. https://doi.org/10.1017/S000711451400052X
4. Mozaffarian D, Appel LJ, Van Horn L (2011) Components of a cardioprotective diet: new insights. Circulation 123(24):2870–2891. https://doi.org/10.1161/CIRCULATIONAHA.110.968735
5. Ajala O, English P, Pinkney J (2013) Systematic review and meta-analysis of different dietary approaches to the management of type 2 diabetes1-3. Am J Clin Nutr 97(3):505–516. https://doi.org/10.3945/ajcn.112.042457

6. Wheeler ML, Dunbar SA, Jaacks LM, Karmally W, Mayer-Davis EJ, Wylie-Rosett J (2010) Yancy WS Jr (2012) Macronutrients, food groups, and eating patterns in the management of diabetes: a systematic review of the literature. Diabetes Care 35(2):434–445. https://doi.org/10.2337/dc11-2216
7. Volpe SL (2013) Magnesium in disease prevention and overall health. Adv Nutr 4(3):378S-383S. https://doi.org/10.3945/an.112.003483
8. Mathe N, Pisa PT, Johnson JA, Johnson ST (2016) Dietary patterns in adults with type 2 diabetes predict cardiometabolic risk factors. Can J Diabetes 40(4):296–303. https://doi.org/10.1016/j.jcjd.2015.11.006
9. WHO Consultation on obesity (1999: Geneva, Switzerland) & World Health Organization (2000) Obesity: preventing and managing the global epidemic: report of a WHO consultation. Available online: https://apps.who.int/iris/handle/10665/42330. (Accessed on 18 Sept 2021)
10. World Health Organization (2008) Waist circumference and waist-hip ratio: report of a WHO expert consultation. Available online: https://www.who.int/publications/i/item/9789241501491. (Accessed 18 Sept 2021)
11. Lohman TJ, Roache AF, Martorell R (1992) Anthropometric standardization reference manual.Med Sci Sports Exerc. Available online: https://doi.org/10.1249/00005768-199208000-00020. (Accessed on 27 Sept 2021)
12. Costa SS, Pereira AC, Passos EA, Alves Jdo P, Garcia CA, Araujo RG (2013) Multivariate optimization of an analytical method for the analysis of dog and cat foods by ICP OES. Talanta 108:157–164. https://doi.org/10.1016/j.talanta.2013.03.002
13. Lowenstein FW, Stanton MF (1986) Serum magnesium levels in the United States, 1971–1974. J Am Coll Nutr 5(4):399–414. https://doi.org/10.1080/07315724.1986.10720143
14. Friedewald WT, Levy RI, Fredrickson DS (1972) Estimation of the concentration of low-density lipoprotein cholesterol in plasma, without use of the preparative ultracentrifuge. Clin Chem 18(6):499–502
15. Oliveira JEPD, Montenegro Junior RM, Vencio S (2017) Diretrizes da Sociedade Brasileira de Diabetes 2017–2018. Editora Clannad, São Paulo
16. Precoma DB, Oliveira GMM, Simao AF, Dutra OP, Coelho OR, Izar MCO, Póvoa RMS, Giuliano ICB, Filho ACA, Machado CA, Scherr C, Fonseca FAH, Filho RDS, Carvalho T, Azevum A, Esposcatte R, Nascimento BR, Brasil DP, Soares PB, Villela RM, et al (2019) Atualização da diretriz de prevenção cardiovascular da Sociedade Brasileira de Cardiologia- 2019. Arq Bras Cardiol. Available online: https://aop-diretriz-prevencao-cardiovascular-portugues.pdf. (cardiol.br) (Accessed on 30 Sept 2021)
17. Moshfegh AJ, Rhodes DG, Baer DJ, Murayi T, Clemens JC, Rumpler WV, Paul DR, Sebastian RS, Kuczynski KJ, Ingwersen LA, Staples RC, Cleveland LE (2008) The US Department of Agriculture Automated Multiple-Pass Method reduces bias in the collection of energy intakes. Am J Clin Nutr 88(2):324–332. https://doi.org/10.1093/ajcn/88.2.324
18. Institute of Medicine (2005) Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids (Macronutrients). Washington, DC: The National Academies Press. Available online: https://nap.nationalacademies.org/catalog/10490/dietary-reference-intakes-for-energy-carbohydrate-fiber-fat-fatty-acids-cholesterol-protein-and-amino-acids. (Accessed on 2 Feb 2022)
19. Institute of Medicine (2006) Dietary reference intakes: the essential guide to nutrient requirements. Washington, DC: The National Academies Press. Available online: https://nap.nationalacademies.org/catalog/11537/dietary-reference-intakes-the-essential-guide-to-nutrient-requirements. (Accessed on 29 Jan 2022)
20. Willett W (2012) Issues in analysis and presentation of dietary data. In: Willet W (ed) Nutritional Epidemiology, 3rd edn. Oxford University Press, Oxford, pp 305–333. https://doi.org/10.1093/acprof:oso/9780199754038.003.0013
21. Oliveira SR, Fisberg RM, Marchioni DM, Baltar VT (2015) Dietary patterns for meals of Brazilian adults. Br J Nutr 114(5):822–828. https://doi.org/10.1017/S0007114515002445
22. Studart EPM, Arruda SPM, Sampaio HAC, Passos TU, Carioca AAF (2018) Dietary patterns and glycemic indexes in type 2 diabetes patients. Rev Nutr 31:1–12. https://doi.org/10.1590/1678-98652018000100001
23. Newby PK, Tucker KL (2004) Empirically derived eating patterns using factor or cluster analysis: a review. Nutr Rev 62(5):177–203. https://doi.org/10.1301/nr.2004.may.177-203
24. Marchioni DML, Latorre MR, Eluf-Neto J, Wünsch-Filho V, Fisberg RM (2005) Identification of dietary patterns using factor analysis in an epidemiological study in São Paulo. Sao Paulo Med J 123(3):124–127. https://doi.org/10.1590/S1516-31802005000300007
25. Vaz JDS, Buffarini R, Kac G, Bielemann RM, Oliveira I, Menezes AB, Assunção MCF (2018) Dietary patterns are associated with blood lipids at 18-year-olds: a cross-sectional analysis nested in the 1993 Pelotas (Brazil) birth cohort. Nutrition 17(1):77. https://doi.org/10.1186/s12937-018-0389-z
26. Bertinato J, Wu Xiao C, Ratnayake WM, Fernandez L, Lavergne C, Wood C, Swist E (2015) Lower serum magnesium concentration is associated with diabetes, insulin resistance, and obesity in South Asian and white Canadian women but not men. Food Nutr Res 59:25974. https://doi.org/10.3402/fnr.v59.25974
27. Bertinato J, Wang KC, Hayward S (2017) Serum magnesium concentrations in the Canadian population and associations with diabetes, glycemic regulation, and insulin resistance. Nutrients 9(3):296. https://doi.org/10.3390/nu9030296
28. Kim DJ, Xun P, Liu K, Loria C, Yokota K, Jacobs DR Jr, He K (2010) Magnesium intake in relation to systemic inflammation, insulin resistance, and the incidence of diabetes. Diabetes Care 33(12):2604–2610. https://doi.org/10.2337/dc10-0994
29. Arpaci D, Tocoglu AG, Ergenc H, Korkmaz S, Ucar A, Tamer A (2015) Associations of serum Magnesium levels with diabetes mellitus and diabetic complications. Hippokratia 19(2):153–157
30. Campbell AP (2017) DASH eating plan: an eating pattern for diabetes management. Diabetes Spectr 30(2):76–81. https://doi.org/10.2337/ds16-0084
31. Sievenpiper JL, Dworatzek PD (2013) Food and dietary pattern-based recommendations: an emerging approach to clinical practice guidelines for nutrition therapy in diabetes. Can J Diabetes 37(1):51–57. https://doi.org/10.1016/j.jcjd.2012.11.001
32. American Diabetes Association (2022) 3. Prevention or delay of type 2 diabetes and associated comorbidities: standards of medical care in diabetes—2022. Diabetes Care 45:S39–S44
33. Dekker LH, van Dam RM, Snijder MB, Peters RJ, Dekker JM, de Vries JH, de Boer EJ, Schulze MB, Stronks K, Nicolaou M (2015) Comparable dietary patterns describe dietary behavior across ethnic groups in the Netherlands, but different elements in the diet are associated with glycated hemoglobin and fasting glucose concentrations. J Nutr 145(8):1884–1891. https://doi.org/10.3945/jn.114.207472
34. Hakeem R, Shiraz M, Riaz M, Fawwad A, Basit A (2018) Association of dietary patterns with glycated haemoglobin among Type 2 diabetics in Karachi, Pakistan. J Diabetol 9(2):59–64. https://https://doi.org/10.4103/jod.jod_4_18
35. Marshall JA, Hoag S, Shetterly S, Hamman RF (1994) Dietary fat predicts conversion from impaired glucose tolerance to NIDDM. The San Luis Valley Diabetes Study. Diabetes Care 17(1):50–56. https://doi.org/10.2337/diacare.17.1.50

36. de la Monte SM, Tong M, Lawton M, Longato L (2009) Nitrosamine exposure exacerbates high fat diet-mediated type 2 diabetes mellitus, non-alcoholic steatohepatitis, and neurodegeneration with cognitive impairment. Mol Neurodegener 4:54. https://doi.org/10.1186/1750-1326-4-54
37. Kellow NJ, Savige GS (2013) Dietary advanced glycation end-product restriction for the attenuation of insulin resistance, oxidative stress and endothelial dysfunction: a systematic review. Eur J Clin Nutr 67(3):239–248. https://doi.org/10.1038/ejcn.2012.220
38. Wolk A (2017) Potential health hazards of eating red meat. J Intern Med 281(2):106–122. https://doi.org/10.1111/joim.12543
39. Buscemi S, Nicolucci A, Mattina A, Rosafio G, Massenti FM, Lucisano G, Galvano F, Amodio E, Pellegrini F, Barile AM, Maniaci V, Grosso G, Verga S, Sprini D, Rini GB (2013) Association of dietary patterns with insulin resistance and clinically silent carotid atherosclerosis in apparently healthy people. Eur J Clin Nutr 67(12):1284–1290. https://doi.org/10.1038/ejcn.2013.172
40. Sadiya A, Mnla R (2019) Impact of food pattern on glycemic control among type 2 diabetic patients: a cross-sectional study in the United Arab Emirates. Diabetes Metab Syndr Obes 12:1143–1150. https://doi.org/10.2147/DMSO.S209320
41. Sarmento RA, Antonio JP, de Miranda IL, Nicoletto BB, Almeida JC (2017) Eating patterns and health outcomes in patients with type 2 diabetes. J Endocr Soc 2(1):42–52. https://doi.org/10.1210/js.2017-00349
42. Satija A, Bhupathiraju SN, Rimm EB, Spiegelman D, Chiuve SE, Borgi L, Willett WC, Manson JE, Sun Q, Hu FB (2016) Plant-based dietary patterns and incidence of type 2 diabetes in US men and women: results from three prospective cohort studies. PLoS Med 13(6):e1002039. https://doi.org/10.1371/journal.pmed.1002039
43. Odegaard AO, Koh WP, Butler LM, Duval S, Gross MD, Yu MC, Yuan JM, Pereira MA (2011) Dietary patterns and incident type 2 diabetes in Chinese men and women the Singapore Chinese Health Study. Diabetes Care 34(4):880–885. https://doi.org/10.2337/dc10-2350
44. Morimoto A, Ohno Y, Tatsumi Y, Mizuno S, Watanabe S (2012) Effects of healthy dietary pattern and other lifestyle factors on incidence of diabetes in a rural Japanese population. Asia Pac J Clin Nutr 21(4):601–608
45. Martín-Peláez S, Fito M, Castaner O (2020) Mediterranean diet effects on type 2 diabetes prevention, disease progression, and related mechanisms. A review. Nutrients 12(8):2236. https://doi.org/10.3390/nu12082236
46. Fardet A, Rock E (2015) From a reductionist to a holistic approach in preventive nutrition to define new and more ethical paradigms. Healthcare (Basel) 3(4):1054–1063. https://doi.org/10.3390/healthcare3041054
47. Perez A, Rojas P, Carrasco F, Basfi-Fer K, Perez-Bravo F, Codoceo J, Inostroza J, Galgani JE, Gilmore LA, Ruz M (2018) Association between zinc nutritional status and glycemic control in individuals with well-controlled type-2 diabetes. J Trace Elem Med Biol 50:560–565. https://doi.org/10.1016/j.jtemb.2018.03.019
48. Sampaio FA, Feitosa MM, Sales CH, Silva DMC, Cruz KJC, Oliveira FE, Colli C, Marreiro DN (2014) Influencia de magnesio en la bioquímicadel hierro y el estrés oxidativo en pacientes con diabetes tipo 2. Nutr Hosp 30:570–576. https://doi.org/10.3305/nh.2014.30.3.7333
49. Shah M, Vasandani C, Adams-Huet B, Garg A (2018) Comparison of nutrient intakes in South Asians with type 2 diabetes mellitus and controls living in the United States. Diabetes Res Clin Pract 138:47–56
50. Brandão-Lima PN, Carvalho GB, Santos RKF, Santos BDC, Dias-Vasconcelos NL, Rocha VS, Barbosa KBF, Pires LV (2018) Intakes of zinc, potassium, calcium, and magnesium of individuals with type 2 diabetes mellitus and the relationship with glycemic control. Nutrients 10(12):1948. https://doi.org/10.3390/nu10121948

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