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Association between phytochemical index and metabolic syndrome

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Conflict of Interest
The authors declare no potential conflicts of
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ABSTRACT

BACKGROUND/OBJECTIVES: Although previous experimental studies reported the health benefits of foods rich in phytochemicals, few epidemiologic studies have investigated the associations between phytochemicals and metabolic disorders. This study aimed to calculate a phytochemical index (PI) and examine its association with metabolic syndrome in the Korean population.

SUBJECTS/METHODS: Data of Korean adults aged ≥ 19 years who participated in the 2008–2016 Korea National Health and Nutrition Examination Surveys were analyzed. The PI was calculated using 24-hour intake recall data regarding whole grains, vegetables, fruits, legumes, nuts and seeds, and soybeans and soy products. Demographic and lifestyle data were obtained using self-administered questionnaires. A multivariable logistic regression was performed to calculate the adjusted odds ratios (ORs) and 95% confidence intervals (CIs) for the prevalence of metabolic syndrome and its components according to PI quintiles.

RESULTS: Overall, 31,319 adults were evaluated. Compared with men, women had a higher median PI level (9.96 vs. 13.63) and significantly higher caloric intake levels from most PI components ($P < 0.05$), except for soy products. After adjusting for multiple confounding variables, participants in the highest PI quintile had significantly lower prevalences of abdominal obesity (OR: 0.90, 95% CI: 0.81–0.99), hyperglycemia (OR: 0.83, 95% CI: 0.74–0.94), high blood pressure (OR: 0.82, 95% CI: 0.73–0.93), hypertriglyceridemia (OR: 0.84, 95% CI: 0.75–0.94), and metabolic syndrome (OR: 0.78, 95% CI: 0.69–0.88).

CONCLUSIONS: Higher intakes of phytochemical-rich foods are associated with a lower prevalence of metabolic dysregulation and consequently, cardiometabolic diseases.

Keywords: Metabolic syndrome; phytochemicals; hyperglycemia; hypertension; Korea

INTRODUCTION

Phytochemicals are plant-derived substances with various known health benefits such as anti-inflammatory, antioxidant, and anticancer effects [1-5]. Previous epidemiologic studies of various populations have demonstrated that the consumption of phytochemical-rich foods can help prevent cardiovascular and metabolic diseases [6-10].

Author Contributions

Conceptualization: Park K, Kim M; Data curation: Kim M; Formal analysis: Kim M; Funding acquisition: Park K; Investigation: Park K, Kim M; Methodology: Park K, Kim M; Project administration: Park K; Resources: Park K; Software: Kim M; Supervision: Park K; Validation: Park K; Visualization: Kim M; Writing - original draft: Kim M; Writing - review & editing: Park K

Recently, a new dietary index, the phytochemical index (PI), was developed to efficiently assess the health effects of phytochemical-rich food intakes in large population-based epidemiologic studies [7,8,11-15]. For example, the Tehran Lipid and Glucose Study calculated a PI based on the daily energy intake derived from phytochemical-rich foods and examined the cross-sectional associations of this index with metabolic risk factors [15-18]. In that study, participants with higher PI values reported a lower prevalence of abdominal obesity and hypertriglyceridemia [16]. Additionally, a recent case-control study of the association between PI and prediabetes reported that a higher PI is significantly associated with a lower risk of prediabetes [19].

There is a paucity of data on the association between the consumption of phytochemical-rich foods and metabolic disorders in the Korean population. To date, the majority of previous Korean studies have solely focused on the effects of specific foods or food groups such as fruits and vegetables [20-22]. Given the increasing prevalences of metabolic syndrome and type 2 diabetes in various Asian countries, including Korea, it is necessary to identify dietary factors that may prevent these diseases and understand their roles in human health. Therefore, the present study aimed to establish a PI for a Korean population and analyze the association between PI and metabolic syndrome using data from the Korea National Health and Nutrition Survey (KNHANES).

SUBJECTS AND METHODS

Data source

The KNHANES is a nationwide cross-sectional health and nutrition survey of non-institutionalized residents of South Korea who are aged ≥ 1 year. All participants provided signed informed consent. Details of this survey have been reported elsewhere [23]. Briefly, survey sampling was conducted using a complex, stratified, multistage, and clustered method. Demographic, lifestyle, dietary, and health data were collected through a health interview, health examination, and nutritional survey. Initially, the KNHANES was first applied as a series of three surveys in 1998, 2001, and 2005. Since 2007, however, the KNHANES has been administered year-round to produce timeline data while excluding seasonal variations.

In this study, we attempted to include all available KNHANES data, including all key variables for the analysis. Regarding these key variables, physical activity questionnaires were not administered in 1998 and 2001, and some details were omitted in 2005. In addition, only 8% of participants responded in 2007. Therefore, this study only analyzed data from the KNHANES during 2008–2016.

The KNHANES was approved by the Institutional Review Board (IRB) of the Korea Centers for Disease Control and Prevention. This entity provided formal ethics approval for the KNHANES data sets (IRB numbers: 2008-04EXP-01-C, 2009-01CON-03-2C, 2010-02CON-21-C, 2011-02CON-06-C, 2012-01EXP-01-2C, 2013-07CON-03-4C, and 2013-12EXP-03-5C).

Participants

Of the 76,909 people who participated in the KNHANES 2008–2016, we excluded the following: (1) those younger than 19 years (n = 17,823); (2) those with missing sampling weight information (n = 9,798); (3) pregnant or lactating women (n = 739); (4) those with

extremely low or high total daily energy intakes (< 500 or > 5,000 kcal; n = 835); (5) patients with known chronic diseases, including hypertension, diabetes, cardiovascular disease, and cancer (n = 14,411); and (6) those with missing data on metabolic biomarkers, including waist circumference (WC), fasting blood sugar, systolic/diastolic blood pressure, triglycerides, or high-density lipoprotein (HDL)-cholesterol levels (n = 1,984). Finally, our analysis included 31,319 participants.

Demographic information

Demographic and lifestyle data were obtained from the questionnaires. These data included age, sex, education level, household income level, job status, obesity status, family history of diabetes, smoking habits, drinking status, and physical activity level. The participants' education levels were reclassified into two categories: lower than high school graduation and high school graduation or higher. The household income levels were categorized into four groups: low, mid-low, mid-high, and high. A positive family history of diabetes was defined as having at least one parent with diabetes. The smoking status was classified into 2 categories: smokers and non-smokers. The daily alcohol intake was calculated by multiplying the servings of alcohol consumed in one sitting by the frequency of consumption. The physical activity level was calculated in terms of metabolic equivalents of task (MET-hours per week) and categorized into tertiles [24].

PI

The PI was calculated using one day (24-hour) recall data collected by trained interviewers who visited participating households during the examination. The following formula was used to calculate the PI: daily energy intake derived from phytochemical-rich foods (kcal) ÷ total daily energy intake (kcal) × 100 [15]. The following food groups were included in the PI calculation: whole grains, vegetables, fruits, legumes, nuts and seeds, and soy products. Fresh soybean products, including tofu, fried tofu, soybean paste, cheonggukjang, and natto, as well as extra virgin olive oil, which is rich in absorbable antioxidants were also included. Considering the high consumption of seaweed among Koreans, we included seaweeds as well in our PI calculation. Generally, fresh fruit and vegetable juices are also included in the calculation. However, the majority of fruit and vegetable juice products consumed by this population are industrially canned or bottled products, which contain low amounts of phytochemicals [25-27]. Accordingly, these products were excluded from the PI calculation. Some grain products with a whole grain content < 50%, potatoes, pickled vegetables (including kimchi), and powdered vegetable and soybean products were also excluded.

Anthropometry and metabolic biomarkers

The body mass index (BMI) was calculated by dividing the body weight (kg) by the square of the height (m²). The BMI cut-off value from the World Health Organization criteria for Asian populations [28] was used to define the following categories: underweight/normal weight (< 23 kg/m²), overweight (≥ 23 to < 25 kg/m²), and obese (≥ 25 kg/m²). WC was measured at the midpoint between the bottom of the least palpable rib and the top of the iliac crest using a stretch-resistant tape.

The participants were asked to fast for at least 8 hours before blood collection. Subsequently, fasting blood samples were sent to a certified laboratory for analyses of the blood glucose, triglyceride, and HDL-cholesterol levels. The laboratory analyses were performed using an ADIVIA 1650 system (Tarrytown, NY, USA) in 2008 and the Hitachi Automatic Analyzer 7600 (Hitachi, Tokyo, Japan) during 2009–2016.

The systolic and diastolic blood pressure were measured twice on the right arm using a mercury sphygmomanometer (Baumanmeter® Desk Model 0320; WA Baum, New York, NY, USA) while the participant was seated. Blood pressure levels were measured thrice, and the average values of the second and third measurements were included in the analysis.

Metabolic syndrome was defined according to the criteria of the modified National Cholesterol Education Program III for the Asian population [29]. Participants who met at least 3 of the following criteria were defined as having metabolic syndrome: (1) a WC ≥ 90 cm in men and ≥ 80 cm in women; (2) fasting glucose level ≥ 100 mg/dL or use of medication for diabetes (insulin or oral agents); (3) triglyceride level ≥ 150 mg/dL or use of lipid-lowering medication; (4) HDL-cholesterol level < 40 mg/dL in men and < 50 mg/dL in women; and (5) blood pressure level ≥ 130/85 mmHg or use of antihypertension medication.

Statistical analysis

Multistage, stratified, and clustered sampling methods were used in the analysis. The age- and total energy-adjusted mean values of daily calorie intakes of the components included in the PI calculation, namely whole grains, vegetables, fruits, legumes, soy products, nuts and seeds, seaweeds, and olive oil, were calculated using a multivariate regression model.

The participants were classified according to PI quintiles, and logistic regression models were used to calculate the odds ratios (ORs) and 95% confidence intervals (CIs) for the association between PI and the prevalence of metabolic syndrome. A preliminary analysis and literature review were conducted to identify potential confounding factors [16-18,30], and effect modifiers were tested using multiplicative terms in the models. Consequently, the following 3 covariate models were constructed: (1) model 1, unadjusted; (2) model 2, adjusted for age and sex; and (3) model 3, additionally adjusted for education, household income level, smoking status, drinking status, and physical activity level. All statistical analyses were performed using SAS software, version 9.4 (SAS Institute, Cary, NC, USA), and the statistical significance level was set at $\alpha = 0.05$.

RESULTS

Intake levels of PI components

Table 1 shows the adjusted mean PI values and calorie intake levels from the food groups used to calculate the PI. The average PI value was higher in women than in men (16.49 ± 0.12 vs. 12.68 ± 0.11, $P < 0.001$). Moreover, the caloric intake levels of all PI components except for soy products were significantly higher in women than in men ($P < 0.05$).

General characteristics of participants according to PI score

Generally, higher PI scores were observed for women, elderly participants, individuals with a higher household income and/or lower education level, non-smokers, non-alcohol drinkers, and obese participants (all $P < 0.01$, **Table 2**). Participants with lower physical activity levels had a significantly lower PI ($P = 0.004$).

Metabolic biomarkers according to PI

Table 3 presents a multivariable-adjusted comparison of metabolic biomarker levels according to the PI value. Notably, significant associations of the fasting blood glucose and triglyceride levels and blood pressure (systolic and diastolic) levels with the PI score were

Table 1. PI and dietary intake levels of food components included in the PI calculation stratified by sex (KNHANES 2008–2016, n = 31,319)

	Sex		P value
	Men	Women	
PI	12.68 ± 0.11	16.49 ± 0.12	< 0.001
Median	9.96	13.63	
Caloric intake levels derived from food groups (kcal)[1]			
Whole grains	64.68 ± 1.43	75.94 ± 1.30	< 0.001
Vegetables	56.33 ± 0.50	59.17 ± 0.50	< 0.001
Fruits	57.97 ± 1.36	104.01 ± 1.98	< 0.001
Legumes	19.69 ± 0.49	21.22 ± 0.48	0.020
Soy products	33.57 ± 0.61	29.19 ± 0.53	< 0.001
Nuts and seeds	14.33 ± 0.53	17.91 ± 0.50	< 0.001
Seaweeds	1.81 ± 0.07	2.09 ± 0.07	0.001
Olive oil	0.74 ± 0.24	1.29 ± 0.25	< 0.001

Values are shown as means ± SE.
PI, phytochemical index; KNHANES, Korea National Health and Nutrition Examination Survey.
[1]Adjusted for age and total energy intake.

observed, and these relationships exhibited a dose-response pattern (P for trend < 0.05). However, the WC and HDL-cholesterol levels did not differ significantly among PI quintiles (WC: P for trend = 0.1, HDL-C: P for trend = 0.5).

Table 2. General characteristics of the participants according to the PI quintiles (KNHANES 2008–2016, n = 31,319)

	Quintile of PI					P value
	Q1	Q2	Q3	Q4	Q5	
No. of participants	6,263	6,264	6,264	6,264	6,264	
PI, median	3.23	7.40	12.04	18.23	30.82	
Sex, men	3,143 (50.18)	2,924 (46.68)	2,582 (41.22)	2,195 (35.04)	1,717 (27.41)	< 0.001
Age (yrs)						< 0.001
19–29	1,654 (26.41)	1,111 (17.74)	917 (14.64)	695 (11.10)	517 (8.25)	
30–39	1,794 (28.64)	1,803 (28.78)	1,522 (24.30)	1,260 (20.11)	991 (15.82)	
40–49	1,223 (19.53)	1,520 (24.27)	1,505 (24.03)	1,547 (24.70)	1,387 (22.14)	
50–59	688 (10.99)	889 (14.19)	1,136 (18.14)	1,350 (21.55)	1,720 (27.46)	
≥ 60	904 (14.43)	941 (15.02)	1,184 (18.90)	1,412 (22.54)	1,649 (26.33)	
Household income[2]						< 0.001
Low	1,872 (30.26)	1,569 (25.33)	1,447 (23.32)	1,290 (20.79)	1,200 (19.32)	
Mid-low	1,610 (26.02)	1,586 (25.61)	1,544 (24.88)	1,540 (24.82)	1,452 (23.38)	
Mid-high	1,468 (23.73)	1,571 (25.36)	1,591 (25.64)	1,641 (26.45)	1,653 (26.61)	
High	1,237 (19.99)	1,468 (23.70)	1,623 (26.16)	1,733 (27.93)	1,906 (30.69)	
Education level[2]						< 0.001
Less than high school graduation	1,336 (22.29)	1,397 (23.19)	1,565 (26.07)	1,684 (28.10)	1,804 (30.16)	
High school graduation or higher	4,658 (77.71)	4,628 (76.81)	4,439 (73.93)	4,309 (71.90)	4,178 (69.84)	
Smoking status[2]						< 0.001
Non-smoker	3,062 (50.32)	3,392 (55.59)	3,755 (61.70)	4,151 (68.17)	4,612 (75.68)	
Smoker	3,023 (49.68)	2,710 (44.41)	2,331 (38.30)	1,938 (31.83)	1,482 (24.32)	
Alcohol consumption (yes)[2]	5,026 (82.79)	4,991 (81.91)	4,712 (77.56)	4,458 (73.33)	4,146 (68.12)	< 0.001
Obesity status[2]						0.008
Underweight/normal	3,192 (51.04)	3,046 (48.69)	3,141 (50.19)	3,095 (49.45)	3,010 (48.08)	
Overweight/obese	3,062 (48.96)	3,210 (51.31)	3,117 (49.81)	3,164 (50.55)	3,250 (51.92)	
Physical activity[1,2]						< 0.001
Low	2,112 (35.21)	2,018 (33.48)	2,049 (34.08)	1,982 (33.06)	1,841 (30.76)	
Middle	1,899 (31.66)	2,002 (33.21)	1,987 (33.05)	2,022 (33.72)	2,141 (35.77)	
High	1,988 (33.14)	2,008 (33.31)	1,977 (32.88)	1,992 (33.22)	2,003 (33.47)	

Values are presented as number of patients (%).
PI, phytochemical index; KNHANES, Korea National Health and Nutrition Examination Survey; Q, quintile.
[1]Physical activity level was calculated as metabolic equivalents of task (MET-hours per week) and grouped into tertiles.
[2]These categories had missing data, and the total n values are not identical.

Table 3. Adjusted average levels of metabolic biomarkers according to the dietary PI quintiles (n = 31,319)

Metabolic syndrome components[1]	Quintile of PI					P for trend
	Q1	Q2	Q3	Q4	Q5	
Waist circumstance (cm)	80.91 ± 0.17	80.76 ± 0.17	80.69 ± 0.17	80.44 ± 0.17	80.62 ± 0.16	0.100
Fasting blood glucose (mg/dL)	94.66 ± 0.27	94.46 ± 0.25	94.47 ± 0.25	93.94 ± 0.26	93.90 ± 0.28	0.020
Triglycerides (mg/dL)	138.14 ± 1.83	135.93 ± 1.94	133.64 ± 1.88	129.56 ± 1.79	126.57 ± 1.57	< 0.001
HDL-cholesterol (mg/dL)	49.58 ± 0.20	49.20 ± 0.20	49.22 ± 0.20	49.18 ± 0.20	49.32 ± 0.21	0.500
Systolic blood pressure (mmHg)	116.39 ± 0.23	115.68 ± 0.24	115.48 ± 0.24	115.10 ± 0.24	115.06 ± 0.25	< 0.001
Diastolic blood pressure (mmHg)	75.44 ± 0.17	75.05 ± 0.17	74.97 ± 0.18	74.57 ± 0.17	74.84 ± 0.17	0.003

PI, phytochemical index; Q, quintile; HDL, high-density lipoprotein.
[1]Values are adjusted for age, sex, education level, household income, smoking status, alcohol drinking, and physical activity level.

Table 4 presents the ORs for abdominal obesity, hyperglycemia, high blood pressure, hypo-HDL cholesterolemia, hyperglyceridemia, and metabolic syndrome according to the PI quintiles. The age- and sex-adjusted models revealed inverse correlations of the PI quintile with the prevalence of abdominal obesity (*P* for trend < 0.001), hyperglycemia (*P* for trend = 0.002), high blood pressure (*P* for trend < 0.001), hypertriglyceridemia (*P* for trend < 0.001), and metabolic syndrome (*P* for trend < 0.001). These inverse linear trends remained statistically significant after adjusting for the additional confounding factors in model 3. Compared with the lowest PI quintile in model 3, participants in the highest (fifth) PI quintile were less likely to present with abdominal obesity (OR: 0.90, 95% CI: 0.81–0.99),

Table 4. ORs (95% CIs) for metabolic syndrome and its components according to the dietary phytochemical index quintiles (n = 31,319)

	Quintile of phytochemical index					P for trend
	Q1	Q2	Q3	Q4	Q5	
	OR	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	
Metabolic syndrome						
No. of case	1,187	1,189	1,200	1,258	1,271	
Model 1	1	1.02 (0.92–1.13)	1.06 (0.95–1.17)	1.06 (0.95–1.18)	1.10 (0.99–1.22)	0.070
Model 2	1	0.89 (0.80–0.99)	0.85 (0.76–0.95)	0.79 (0.70–0.88)	0.76 (0.68–0.84)	< 0.001
Model 3	1	0.88 (0.78–0.98)	0.87 (0.77–0.97)	0.82 (0.73–0.92)	0.78 (0.69–0.88)	< 0.001
Abdominal obesity						
No. of case	1,735	1,783	1,853	1,951	2,087	
Model 1	1	1.07 (0.97–1.18)	1.12 (1.02–1.23)	1.17 (1.07–1.29)	1.30 (1.19–1.43)	< 0.001
Model 2	1	0.96 (0.87–1.06)	0.91 (0.82–1.00)	0.87 (0.79–0.96)	0.87 (0.79–0.96)	0.001
Model 3	1	0.97 (0.87–1.07)	0.93 (0.84–1.03)	0.90 (0.81–0.99)	0.90 (0.81–0.99)	0.020
Hyperglycemia						
No. of case	1,281	1,341	1,353	1,403	1,408	
Model 1	1	1.08 (0.97–1.20)	1.11 (1.00–1.23)	1.16 (1.04–1.28)	1.16 (1.04–1.28)	0.004
Model 2	1	0.93 (0.83–1.04)	0.90 (0.81–0.99)	0.88 (0.79–0.98)	0.83 (0.74–0.93)	0.002
Model 3	1	0.91 (0.81–1.02)	0.91 (0.81–1.01)	0.87 (0.78–0.98)	0.83 (0.74–0.94)	0.003
High blood pressure						
No. of case	1,359	1,394	1,376	1,384	1,371	
Model 1	1	1.04 (0.94–1.15)	1.07 (0.97–1.19)	0.97 (0.88–1.08)	1.01 (0.91–1.13)	0.700
Model 2	1	0.94 (0.84–1.04)	0.92 (0.82–1.02)	0.80 (0.71–0.89)	0.80 (0.72–0.90)	< 0.001
Model 3	1	0.93 (0.83–1.04)	0.92 (0.82–1.03)	0.81 (0.72–0.91)	0.82 (0.73–0.93)	< 0.001
Hypo-HDL cholesterolemia						
No. of case	2,088	2,217	2,234	2,399	2,441	
Model 1	1	1.11 (1.01–1.21)	1.14 (1.04–1.25)	1.28 (1.16–1.40)	1.37 (1.25–1.50)	< 0.001
Model 2	1	1.02 (0.93–1.13)	0.98 (0.89–1.07)	1.01 (0.92–1.12)	0.995 (0.90–1.10)	0.900
Model 3	1	1.06 (0.96–1.16)	1.01 (0.92–1.11)	1.07 (0.97–1.18)	1.04 (0.94–1.15)	0.500
Hypertriglyceridemia						
No. of case	1,708	1,708	1,622	1,595	1,567	
Model 1	1	1.03 (0.94–1.13)	0.94 (0.86–1.03)	0.89 (0.81–0.97)	0.86 (0.78–0.94)	< 0.001
Model 2	1	0.95 (0.86–1.04)	0.86 (0.78–0.94)	0.81 (0.73–0.89)	0.80 (0.72–0.88)	< 0.001
Model 3	1	0.94 (0.85–1.04)	0.87 (0.79–0.96)	0.86 (0.77–0.95)	0.84 (0.75–0.94)	0.001

Model 1: unadjusted, Model 2: adjustment for age and sex, Model 3: model 2 plus additional adjustments for education level, household income, smoking status, alcohol consumption, and physical activity level.
OR, odds ratio; CI, confidence interval; Q, quintile; HDL, high-density lipoprotein.

hyperglycemia (OR: 0.83, 95% CI: 0.74–0.94), high blood pressure (OR: 0.82, 95% CI: 0.73–0.93), hypertriglyceridemia (OR: 0.84, 95% CI: 0.75–0.94), and metabolic syndrome (OR: 0.78, 95% CI: 0.69–0.88).

DISCUSSION

In this study, we observed that higher PI levels were associated with a lower prevalence of various forms of metabolic dysregulation, including abdominal obesity, hyperglycemia, high blood pressure, hypertriglyceridemia, and metabolic syndrome. In this population, whole grains, vegetables, and fruits were major food sources contributing to PI. Generally, women consumed larger amounts of whole grains, vegetables, fruits, nuts and seeds, and olive oil than men and therefore, tended to have higher PI values.

Many studies have emphasized the health benefits of consuming foods rich in phytochemicals [16,18,30]. According to the Tehran Lipid and Glucose Study, a higher PI was associated with lower WC, systolic and diastolic blood pressure, and triglyceride levels, as well as significantly lower risks of abdominal obesity and hypertriglyceridemia [16]. In another study, Bahadoran *et al.* [30] reported that a higher PI was associated with reductions of 86%, 52%, and 89% in the risks of hyperinsulinemia, insulin resistance, and insulin insensitivity, respectively. One previous study of the associations between PI and blood lipid levels reported significantly better total blood lipid, total cholesterol, and non-HDL-cholesterol concentrations in men with a higher PI [18].

Some researchers have attributed the biological mechanisms underlying the occurrence of metabolic syndrome to insulin resistance and obesity [31]. In a person with insulin resistance, the body does not respond normally to secreted insulin [32], thus leading to hyperinsulinemia and subsequent development of other cardiometabolic risk factors such as high blood pressure and dyslipidemia, which are also known risk factors for metabolic syndrome [33]. The cumulative evidence associates the consumption of phytochemicals abundant in plant-based foods, particularly polyphenols, with improvements in insulin resistance [34]. Specifically, polyphenols regulate insulin production and secretion and protect pancreatic β-cells from oxidative stress [34,35]. Moreover, some polyphenols increase insulin-dependent glucose uptake in the context of insulin resistance by inducing the cell membrane localization of GLUT4 via the activation of AMP-activated protein kinase, a signal transducer involved in insulin secretion from β-cells [34,36]. The beneficial flavonoid quercetin contributes to reductions in blood pressure, visceral fat, and body fat and promotes the apoptosis of adipocytes, while genistein is associated with decreases in BMI and fat mass and increases in HDL-cholesterol and glucose tolerance [37].

This study had several strengths. For example, the use of data from the KNHANES, a South Korean nationally representative cross-sectional survey, enhanced the generalizability of our results. Moreover, to the best of our knowledge, this was the first study to examine the effects of the magnitude of phytochemical intake on metabolic health in a Korean population. However, this study also has some limitations to note. First, the association between PI and metabolic syndrome was analyzed using cross-sectional data, and therefore causality could not be determined. To minimize the possibility of reverse causality, we excluded patients who were aware of their chronic disease statuses and thus, could have changed their diet or lifestyle habits after diagnosis. Second, we calculated PI using one day (24-hour) recall data,

which might not have reflected the participants' usual intake levels accurately. PI was also calculated using calories from consumed food items, and therefore food items containing zero calories could not be included. Despite these limitations, however, PI appears to be a useful surrogate index of phytochemical intake level with a confirmed predictive validity.

In conclusion, we determined an association of our newly calculated PI with metabolic syndrome in a sample of Korean adults. Our findings support dietary guidelines that emphasize intake of phytochemical-rich foods. Large-scale prospective cohort studies or randomized clinical trials are warranted to confirm our findings.

REFERENCES

1. Martinez KB, Mackert JD, McIntosh MK. Polyphenols and intestinal health. In: Watson RR, editor. Nutrition and Functional Foods for Healthy Aging. Cambridge: Academic Press; 2017. p.191-210.

2. Surh YJ. Cancer chemopreventive effects of dietary phytochemicals. J Korean Assoc Cancer Prev 2004;9:68-83.

3. Kocyigit A, Guler EM, Dikilitas M. Role of antioxidant phytochemicals in prevention, formation and treatment of cancer. In: Cristiana F, editor. Reactive Oxygen Species (ROS) in Living Cells. London: InterchOpen; 2018. p.21-45.

4. Liu RH. Potential synergy of phytochemicals in cancer prevention: mechanism of action. J Nutr 2004;134:3479S-3485S.
   PUBMED | CROSSREF

5. Zhang H, Tsao R. Dietary polyphenols, oxidative stress and antioxidant and anti-inflammatory effects. Curr Opin Food Sci 2016;8:33-42.
   CROSSREF

6. Liu S, Manson JE, Stampfer MJ, Rexrode KM, Hu FB, Rimm EB, Willett WC. Whole grain consumption and risk of ischemic stroke in women: a prospective study. JAMA 2000;284:1534-40.
   PUBMED | CROSSREF

7. Wang PY, Fang JC, Gao ZH, Zhang C, Xie SY. Higher intake of fruits, vegetables or their fiber reduces the risk of type 2 diabetes: a meta-analysis. J Diabetes Investig 2016;7:56-69.
   PUBMED | CROSSREF

8. Juan J, Liu G, Willett WC, Hu FB, Rexrode KM, Sun Q. Whole grain consumption and risk of ischemic stroke: results from 2 prospective cohort studies. Stroke 2017;48:3203-9.
   PUBMED | CROSSREF

9. Aune D, Keum N, Giovannucci E, Fadnes LT, Boffetta P, Greenwood DC, Tonstad S, Vatten LJ, Riboli E, Norat T. Nut consumption and risk of cardiovascular disease, total cancer, all-cause and cause-specific mortality: a systematic review and dose-response meta-analysis of prospective studies. BMC Med 2016;14:207.
   PUBMED | CROSSREF

10. Bazzano LA, He J, Ogden LG, Loria C, Vupputuri S, Myers L, Whelton PK. Legume consumption and risk of coronary heart disease in US men and women: NHANES I Epidemiologic Follow-up Study. Arch Intern Med 2001;161:2573-8.
    PUBMED | CROSSREF

11. Parker ED, Liu S, Van Horn L, Tinker LF, Shikany JM, Eaton CB, Margolis KL. The association of whole grain consumption with incident type 2 diabetes: the Women's Health Initiative Observational Study. Ann Epidemiol 2013;23:321-7.
    PUBMED | CROSSREF

12. Villegas R, Shu XO, Gao YT, Yang G, Elasy T, Li H, Zheng W. Vegetable but not fruit consumption reduces the risk of type 2 diabetes in Chinese women. J Nutr 2008;138:574-80.
    PUBMED | CROSSREF

13. Albert CM, Gaziano JM, Willett WC, Manson JE. Nut consumption and decreased risk of sudden cardiac death in the Physicians' Health Study. Arch Intern Med 2002;162:1382-7.
    PUBMED | CROSSREF

14. Misirli G, Benetou V, Lagiou P, Bamia C, Trichopoulos D, Trichopoulou A. Relation of the traditional Mediterranean diet to cerebrovascular disease in a Mediterranean population. Am J Epidemiol 2012;176:1185-92.
    PUBMED | CROSSREF

15. McCarty MF. Proposal for a dietary "phytochemical index". Med Hypotheses 2004;63:813-7.
    PUBMED | CROSSREF

16. Bahadoran Z, Golzarand M, Mirmiran P, Saadati N, Azizi F. The association of dietary phytochemical index and cardiometabolic risk factors in adults: Tehran Lipid and Glucose Study. J Hum Nutr Diet 2013;26 Suppl 1:145-53.
    PUBMED | CROSSREF

17. Golzarand M, Bahadoran Z, Mirmiran P, Sadeghian-Sharif S, Azizi F. Dietary phytochemical index is inversely associated with the occurrence of hypertension in adults: a 3-year follow-up (the Tehran Lipid and Glucose Study). Eur J Clin Nutr 2015;69:392-8.
    PUBMED | CROSSREF

18. Golzarand M, Mirmiran P, Bahadoran Z, Alamdari S, Azizi F. Dietary phytochemical index and subsequent changes of lipid profile: a 3-year follow-up in Tehran Lipid and Glucose Study in Iran. ARYA Atheroscler 2014;10:203-10.
    PUBMED

19. Abshirini M, Mahaki B, Bagheri F, Siassi F, Koohdani F, Sotoudeh G. Higher intake of phytochemical-rich foods is inversely related to prediabetes: a case-control study. Int J Prev Med 2018;9:64.
    PUBMED | CROSSREF

20. Yuan C, Lee HJ, Shin HJ, Stampfer MJ, Cho E. Fruit and vegetable consumption and hypertriglyceridemia: Korean National Health and Nutrition Examination Surveys (KNHANES) 2007–2009. Eur J Clin Nutr 2015;69:1193-9.
    PUBMED | CROSSREF

21. Lee YJ, Nam GE, Seo JA, Yoon T, Seo I, Lee JH, Im D, Bahn KN, Jeong SA, Kang TS, Ahn JH, Kim DH, Kim NH. Nut consumption has favorable effects on lipid profiles of Korean women with metabolic syndrome. Nutr Res 2014;34:814-20.
    PUBMED | CROSSREF

22. Hong SA, Kim MK. Relationship between fruit and vegetable intake and the risk of metabolic syndrome and its disorders in Korean women according to menopausal status. Asia Pac J Clin Nutr 2017;26:514-23.
    PUBMED

23. Kweon S, Kim Y, Jang MJ, Kim Y, Kim K, Choi S, Chun C, Khang YH, Oh K. Data resource profile: the Korea National Health and Nutrition Examination Survey (KNHANES). Int J Epidemiol 2014;43:69-77.
    PUBMED | CROSSREF

24. Ainsworth BE, Haskell WL, Leon AS, Jacobs DR Jr, Montoye HJ, Sallis JF, Paffenbarger RS Jr. Compendium of physical activities: classification of energy costs of human physical activities. Med Sci Sports Exerc 1993;25:71-80.
    PUBMED | CROSSREF

25. Bhagwat S, Haytowitz D. USDA Database for the proanthocyanidin content of selected foods release 2 [Internet]. Washington, D.C.: United States Department of Agriculture; 2015 [cited 18 November 2018]. Available from: https://data.nal.usda.gov/dataset/usda-database-proanthocyanidin-content-selected-foods-release-2-2015.

26. Bhagwat S, Haytowitz DB. USDA database for the isoflavone content of selected foods release 2.1 [Internet]. Washington, D.C.: United States Department of Agriculture; 2015 [cited 18 November 2018]. Available from: https://data.nal.usda.gov/dataset/usda-database-isoflavone-content-selected-foods-release-21-november-2015.

27. Bhagwat S, Haytowitz DB. USDA database for the flavonoid content of selected foods release 3.2 [Internet]. Washington, D.C.: United States Department of Agriculture; 2015 [cited 18 November 2018]. Available from: https://data.nal.usda.gov/dataset/usda-database-flavonoid-content-selected-foods-release-32-november-2015.

28. World Health Organization. The Asia Pacific perspective: redefining obesity and its treatment [Internet]. Sydney: Health Communications Australia; 2000 [cited 9 November 2018]. Available from: www.wpro.who.int/nutrition/documents/.../Redefiningobesity.pdf.

29. Grundy SM, Cleeman JI, Daniels SR, Donato KA, Eckel RH, Franklin BA, Gordon DJ, Krauss RM, Savage PJ, Smith SC Jr, Spertus JA, Costa FAmerican Heart AssociationNational Heart, Lung, and Blood Institute. Diagnosis and management of the metabolic syndrome: an American Heart Association/National Heart, Lung, and Blood Institute Scientific Statement. Circulation 2005;112:2735-52.
    PUBMED | CROSSREF

30. Bahadoran Z, Mirmiran P, Tohidi M, Azizi F. Dietary phytochemical index and the risk of insulin resistance and β-cell dysfunction: a prospective approach in Tehran Lipid and Glucose Study. Int J Food Sci Nutr 2015;66:950-5.
    PUBMED | CROSSREF

31. Reaven GM. Banting lecture 1988. Role of insulin resistance in human disease. Diabetes 1988;37:1595-607.
    PUBMED | **CROSSREF**

32. Wilcox G. Insulin and insulin resistance. Clin Biochem Rev 2005;26:19-39.
    PUBMED

33. Schrezenmeir J. Hyperinsulinemia, hyperproinsulinemia and insulin resistance in the metabolic syndrome. Experientia 1996;52:426-32.
    PUBMED | **CROSSREF**

34. Bahadoran Z, Mirmiran P, Azizi F. Dietary polyphenols as potential nutraceuticals in management of diabetes: a review. J Diabetes Metab Disord 2013;12:43.
    PUBMED | **CROSSREF**

35. Zhang B, Kang M, Xie Q, Xu B, Sun C, Chen K, Wu Y. Anthocyanins from Chinese bayberry extract protect β cells from oxidative stress-mediated injury via HO-1 upregulation. J Agric Food Chem 2011;59:537-45.
    PUBMED | **CROSSREF**

36. Park CE, Kim MJ, Lee JH, Min BI, Bae H, Choe W, Kim SS, Ha J. Resveratrol stimulates glucose transport in C2C12 myotubes by activating AMP-activated protein kinase. Exp Mol Med 2007;39:222-9.
    PUBMED | **CROSSREF**

37. Holubková A, Penesová A, Šturdík E, Mošovská S, Mikušová L. Phytochemicals with potential effects in metabolic syndrome prevention and therapy. Acta Chim Slov 2012;5:186-99.
    CROSSREF