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Plant-Based Dietary Patterns and Incident Diabetes in the Atherosclerosis Risk in Communities (ARIC) Study

Valerie K. Sullivan, Hyunju Kim, Laura E. Caulfield, Lyn M. Steffen, Elizabeth Selvin, and Casey M. Rebholz

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Study Population

- Middle-aged adults
- Black and White race
- 4 U.S. communities
- Without diabetes

ARIC n=11,965

Exposure

↑ *Higher* intakes receive higher scores

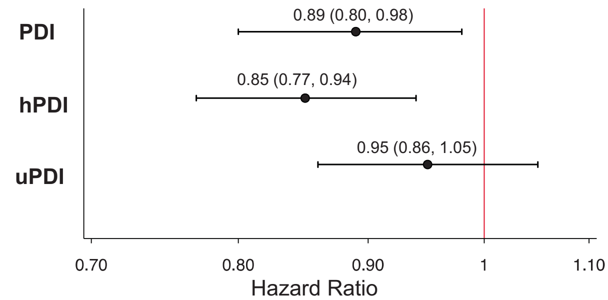
↓ *Lower* intakes receive higher scores

Component	PDI	hPDI	uPDI
Whole grains	↑	↑	↓
Fruits	↑	↑	↓
Vegetables	↑	↑	↓
Nuts	↑	↑	↓
Legumes	↑	↑	↓
Coffee & tea	↑	↑	↓
Fruit juice	↑	↓	↑
Refined grains	↑	↓	↑
Potatoes	↑	↓	↑
Sugar-sweetened beverages	↑	↓	↑
Sweets	↑	↓	↑
Animal fats	↓	↓	↓
Dairy	↓	↓	↓
Meat	↓	↓	↓
Eggs	↓	↓	↓
Fish	↓	↓	↓

PDI, plant-based diet index;
hPDI, healthy PDI; uPDI, unhealthy PDI

Outcome: Type 2 Diabetes

- Self-reported diagnosis, or
- Use of diabetes medications, or
- Fasting blood glucose ≥126 mg/dL, or
- Nonfasting blood glucose ≥200 mg/dL



Quintile 5 versus 1. Adjusted for age, sex, race-center, energy intake, education, income, physical activity, smoking status, margarine intake, and alcohol intake.

- Greater adherence to a plant-based dietary pattern was associated with a lower risk of incident diabetes.
- A dietary pattern that minimizes animal-derived foods and emphasizes plant foods may reduce diabetes risk.

ARTICLE HIGHLIGHTS

- **Why did we undertake this study?**
  Plant-based dietary patterns, which primarily consist of plant foods and minimize animal-derived foods, have been associated with lower risk of diabetes in select populations.
- **What is the specific question(s) we wanted to answer?**
  We investigated the generalizability of this association in the Atherosclerosis Risk in Communities study relative to prior research.
- **What did we find?**
  Greater adherence to an overall and healthy plant-based dietary pattern was associated with a lower risk of incident diabetes.
- **What are the implications of our findings?**
  Emphasizing intake of plant-derived foods while minimizing animal-derived foods may be an effective dietary strategy to prevent diabetes.

ORIGINAL ARTICLE

Plant-Based Dietary Patterns and Incident Diabetes in the Atherosclerosis Risk in Communities (ARIC) Study

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OBJECTIVE

Plant-based dietary patterns emphasize plant foods and minimize animal-derived foods. We investigated the association between plant-based dietary patterns and diabetes in a community-based U.S. sample of Black and White adults.

RESEARCH DESIGN AND METHODS

We included middle-aged adults from the Atherosclerosis Risk in Communities (ARIC) study without diabetes at baseline who completed a food-frequency questionnaire (n = 11,965). We scored plant-based diet adherence according to three indices: overall, healthy, and unhealthy plant-based diet indices. Higher overall plant-based diet index (PDI) scores represent greater intakes of all plant foods and lower intakes of animal-derived foods. Higher healthy plant-based diet index (hPDI) scores represent greater healthy plant food intake and lower intakes of animal-derived and unhealthy plant foods. Higher unhealthy plant-based diet index (uPDI) scores represent greater unhealthy plant food intake and lower intakes of animal-derived and healthy plant foods. We used Cox regression to estimate hazard ratios (HRs) for incident diabetes (defined according to self-reported diagnosis, medication use, or elevated blood glucose) associated with each index.

RESULTS

Over a median follow-up of 22 years, we identified 4,208 cases of diabetes among subjects. Higher PDI scores were associated with a lower risk of diabetes (quintile 5 vs. 1 HR 0.89 [95% CI 0.80, 0.98]; P_{trend} = 0.01). hPDI scores were also inversely associated with diabetes risk (quintile 5 vs. 1 HR 0.85 [95% CI 0.77, 0.94]; P_{trend} < 0.001). uPDI scores were not associated with diabetes risk.

CONCLUSIONS

A dietary pattern that minimizes animal-derived foods and emphasizes plant foods may reduce diabetes risk.

Poor diet is an important risk factor contributing to the burden of diabetes (1,2). People adhering to vegan and vegetarian dietary patterns, which exclude all or certain types of animal-derived foods, have a lower risk of developing diabetes (3,4). Of U.S. adults, <5% identify as vegan or vegetarian (5), and elimination of animal products may not be acceptable to most Americans (6). Thus, "plant-based" dietary patterns, which

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See accompanying article, p. 787.

primarily consist of plant foods and minimize (without excluding) animal-derived foods, may be a feasible dietary strategy to prevent diabetes.

In prior studies in primarily White educated health professionals, higher adherence to a plant-based diet was associated with a lower risk of developing type 2 diabetes (7). The generalizability of these findings to the broader U.S. population is uncertain. Among Puerto Rican adults in Boston, for instance, adherence to a plant-based diet was not associated with diabetes risk (8). However, a healthy plant-based diet that specifically emphasized intake of vegetables, fruits, nuts, legumes, whole grains, vegetable oils, tea and coffee, and minimized intake of refined and sweetened plant foods, was associated with a lower risk of developing diabetes in this population (8). The quantity and quality of plant foods consumed, and their associations with diabetes risk, may differ across population subgroups.

We investigated the associations between plant-based diets and diabetes risk in the Atherosclerosis Risk in Communities (ARIC) study, which included Black and White adults with varied education and income levels from four U.S. geographic regions. We hypothesized that greater adherence to an overall plant-based diet and a healthy plant-based diet would be associated with lower risk of developing diabetes, whereas greater adherence to a less healthful plant-based diet would be associated with a higher risk of diabetes.

RESEARCH DESIGN AND METHODS

Study Design and Population

The ARIC study is a community-based prospective study that enrolled 15,792 adults aged 45–64 years from four U.S. communities (Washington County, MD, Forsyth County, NC, Minneapolis, MN, and Jackson, MS) in 1987–1989 (visit 1) (9). Participants attended in-person follow-up clinic visits in 1990–1992 (visit 2), 1993–1995 (visit 3), 1996–1998 (visit 4), 2011–2013 (visit 5), 2016–2017 (visit 6), 2018–2019 (visit 7), and 2022 (visit 9). Visit 8 (2020–2021) was conducted remotely during the coronavirus disease 2019 pandemic. After visit 4, participants were also contacted by telephone annually until 2012 and semiannually thereafter. The institutional review board at each study site approved the study protocol, and participants provided informed consent.

For the 15,792 participants examined at visit 1, we excluded those who withdrew consent, those with prevalent diabetes (defined according to self-reported physician diagnosis, use of diabetes medications, fasting blood glucose $\geq$126 mg/dL, or nonfasting blood glucose $\geq$200 mg/dL), and those with missing diabetes status at baseline (Supplementary Fig. 1). We also excluded those with self-reported history of coronary heart disease, cancer, or stroke, as people may have changed their diets after developing these health conditions. We further excluded people with implausible energy intakes (women $<$500 or $>$3,500 kcal, men $<$600 or $>$4,500 kcal) or missing $>$10 items on the food-frequency questionnaire. We excluded the small number of participants who were neither Black nor White. Finally, we excluded participants who were missing any covariates except income, for which a missing income category was created. The sample for analysis included 11,965 participants.

Diet Assessment

Trained interviewers assessed participants' dietary intakes at visits 1 and 3 using a 66-item modified version of the semiquantitative Willett questionnaire (10). Participants reported the frequency with which they consumed a specified portion of each item in the previous year. Nutrient intakes were estimated with multiplication of the frequency of reported intake by the nutrient content of each item according to U.S. Department of Agriculture data. From visit 1 until visit 3, diabetes risk was calculated in relation to visit 1 dietary intakes. From visit 3 onward, we averaged questionnaire responses from both visits to estimate usual intake (11).

Plant-Based Diet Scores

We scored adherence to a plant-based diet according to three indices: an overall plant-based diet index (PDI), a healthy plant-based diet index (hPDI), and an unhealthy plant-based diet index (uPDI) (7). Calculation of these scores in the ARIC study has previously been described (12). Briefly, we classified items as animal foods (animal fat, dairy, eggs, fish and seafood, meat, miscellaneous animal-based mixed dishes), healthy plant foods (fruits, vegetables, whole grains, nuts, legumes, tea and coffee), and unhealthy plant foods (fruit juices, refined grains, potatoes, sugar-sweetened and low-calorie or diet beverages, sweets). The distinction of healthy versus unhealthy plant foods in the original indices was based on their associations with chronic disease risk (7). Margarine was excluded from score calculations, as margarine available during the years for which diet was assessed may have been high in *trans* fat. Instead, we adjusted for margarine intake as a covariate (7).

We calculated energy-adjusted intake of all 17 food groups using the residual method and then categorized intake into quintiles. For all indices, animal foods were reverse scored, such that quintile 1 (lowest intakes) was assigned 5 points and quintile 5 (highest intakes) was assigned 1 point. Each index scored plant foods differently. For the PDI, all plant foods were scored positively, such that quintile 1 was assigned 1 point and quintile 5 was assigned 5 points. The hPDI positively scored intakes of healthy plant foods and reverse scored unhealthy plant foods. Opposite, the uPDI assigned higher point values for higher intakes of unhealthy plant foods and reverse scored intakes of healthy plant foods. Possible scores for all indices ranged from 17 to 85, with higher values representing greater adherence to a plant-based diet.

Incident Diabetes Ascertainment

Incident diabetes was defined according to any one of the following criteria: self-reported diagnosis by a health care provider, current diabetes medication use, 8-h fasting serum glucose $\geq$126 mg/dL, or nonfasting serum glucose $\geq$200 mg/dL. Self-reported diabetes diagnosis was assessed at study visits (all except visit 5) and through telephone interviews. Use of diabetes medications was self-reported at all study visits and telephone interviews. Medication bottles were also reviewed and scanned by study staff at all study visits. Serum glucose concentrations were assessed from blood specimens collected at all study visits with the hexokinase–glucose-6-phosphate dehydrogenase method (13).

Covariate Assessment

Sociodemographic information, smoking status, and physical activity were self-reported at study visits. Physical activity was assessed with a modified Baecke questionnaire, with leisure-time sport activity expressed as a score ranging from 1 (least active) to 5 (most active) (14,15). BMI was assessed at all study visits as weight in kilograms divided by the square of height in meters.

Statistical Analyses

Mean ± SD and proportions for baseline characteristics and nutrient intakes were examined according to quintiles of plant-based diet scores. We assessed associations between plant-based diet indices and diabetes incidence using covariate-adjusted Cox proportional hazards models, with time on study as the time metric. Follow-up time was calculated from visit 1 until death or date of last known diabetes status prior to 31 December 2020. We calculated hazard ratios (HR) and 95% CIs according to quintiles of plant-based diet scores, with quintile 1 as the reference. A minimally adjusted model (model 1) included adjustment for age (continuous), sex, race-center (a variable representing race and study center), and total energy intake (continuous). The primary model (model 2) included additional adjustment for education (less than high school, high school graduate, postsecondary education), income (<US$5,000, $5,000–7,999, $8,000–11,999, $12,000–15,999, $16,000–24,999, $25,000–34,999, $35,000–49,999, >$50,000, or missing), smoking status (current, former, never), physical activity (continuous), margarine intake (continuous), and alcohol intake (quartiles). We additionally adjusted for baseline BMI (continuous) in model 3 to examine the potential mediating effect of BMI. Diet was updated at visit 3 with use of the cumulative average of visit 1 and visit 3 questionnaire responses. Smoking status, physical activity, and BMI were updated with visit 3 responses; missing values at visit 3 were carried forward from visit 1. We assessed continuous associations per 10-unit-higher PDI score and explored the shape of the associations using restricted cubic splines.

We assessed the robustness of associations across subgroups defined by sex, age (≤54 and >54 years [median]), race (White vs. Black), and BMI (<25, 25 to <30, and ≥30 kg/m^2) using likelihood ratio tests comparing results from model 2 with versus without an interaction term. We evaluated the statistical significance of interactions using a Bonferroni-adjusted *P* value = 0.05/12 (3 indices × 4 subgroups) = 0.004.

As a sensitivity analysis for understanding of whether associations were driven by individual components of the plant-based diet indices, we recalculated scores by removing 1 of the 17 components at a time and instead controlled for energy-adjusted intakes of the excluded components. We also examined associations after excluding all animal components except red meat. We controlled for energy-adjusted intakes of excluded animal components in these models. In another sensitivity analysis, we adjusted for time-varying BMI updated using BMI measured at each clinic visit. For missing BMI values, the last measured value was carried forward. In another sensitivity analysis, we excluded the first 5 years of follow-up and diabetes diagnoses that occurred during that time to reduce the influence of reverse causation. Finally, we reassessed associations using a more specific definition of incident treated diabetes based on medication use only.

Analyses were performed with Stata, version 16.1 (StataCorp). All statistical tests were two sided with a 0.05 level of significance.

Data and Resource Availability

The data sets analyzed in the current study are available on reasonable request from the ARIC coordinating center or the National Heart, Lung, and Blood Institute (NHLBI) Biologic Specimen and Data Repository Information Coordinating Center.

RESULTS

Baseline Characteristics and Nutrient Intakes

Scores for the PDI ranged from 27 to 74, hPDI from 28 to 75, and uPDI from 28 to 78. Compared with those in the lowest quintile, individuals in the highest quintile of the PDI were more likely to be women, White, high school graduates, and never smokers with higher income and physical activity and lower BMI (Table 1). In comparison with individuals in the lowest quintile, those in the highest PDI quintile consumed a lower percentage of energy from total, saturated, and monounsaturated fat, and protein; a higher percentage of energy from carbohydrates; and more dietary fiber, potassium, and sodium. Mean daily total plant and animal food intakes for quintile 5 were 15.1 and 3.4 servings per day, respectively, whereas average consumption for quintile 1 was 9.9 servings of plant foods and 5.8 servings of animal foods per day.

Similar trends were observed across hPDI quintiles, except that protein intakes did not notably differ in comparing extreme quintiles (Supplementary Table 1). Participants with the highest uPDI scores were more likely to be men and to smoke and less likely to have graduated high school compared with those with the lowest scores. They also had lower protein, fiber, potassium, and sodium intakes and higher carbohydrate intakes (Supplementary Table 2).

Plant-Based Diets and Incident Diabetes

During a median follow-up of 22 years, 4,208 participants (35%) developed diabetes. With model 1, controlling for age, sex, race-center, and energy intake, individuals in the highest quintile of PDI scores had a 14% (95% CI 5–22) lower risk of developing diabetes, compared with the lowest quintile (Table 2). The association was attenuated by adjustment for additional sociodemographic (education and income), lifestyle (smoking, alcohol intake, and physical activity), and dietary (margarine intake) covariates (model 2, quintile 5 vs. 1 HR 0.89 [95% CI 0.80, 0.98]; P_{trend} = 0.01). Examined as a continuous score, each 10-point higher PDI score was associated with a 6% lower risk of diabetes (95% CI 1–11), and the association was approximately linear (Fig. 1). The inverse association between PDI scores with incident diabetes was attenuated by adjustment for BMI (model 3; P_{trend} = 0.23).

Higher hPDI scores were also inversely associated with diabetes risk in the minimally adjusted model (model 1, quintile 5 vs. 1 HR 0.79 [95% CI 0.71, 0.87]; $P_{trend} < 0.001$) and in the main model (model 2, quintile 5 vs. 1 HR 0.85 [95% CI 0.77, 0.94]; $P_{trend} < 0.001$), and the association appeared to be linear (model 2, HR per 10 units higher 0.90 [95% CI 0.86, 0.95]) (Supplementary Fig. 2 and Table 2). The inverse association was attenuated but remained significant after adjustment for BMI (model 3 [P_{trend} = 0.04]).

Higher uPDI scores were not significantly associated with diabetes risk in any model (for models 1, 2, and 3 $P_{trend} > 0.05$) (Supplementary Fig. 3 and Table 2).

Associations between plant-based diet scores and diabetes did not differ by sex,

Table 1—Baseline characteristics and dietary intakes by quintile of PDI score in the ARIC study (*n* = 11,965)

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
n	2,761	2,805	2,252	1,977	2,170
Score, median (range)	44 (27–46)	49 (47–50)	52 (51–53)	55 (54–56)	59 (57–74)
Age, years	53 ± 6	53 ± 6	54 ± 6	54 ± 6	54 ± 6
Women	45	55	58	63	64
Race					
Black	38	30	22	19	12
White	62	70	78	81	88
High school graduate	71	77	81	82	86
Income					
≥US$50,000	20	23	28	28	30
Missing	6	6	6	5	5
Smoking status, %					
Current	33	28	25	22	19
Never	38	41	44	45	47
Physical activity index	2.3 ± 0.8	2.4 ± 0.8	2.5 ± 0.8	2.5 ± 0.8	2.6 ± 0.8
BMI (kg/m^2)	27.9 ± 5.4	27.5 ± 5.3	27.2 ± 4.9	27.0 ± 5.0	26.7 ± 5.0
BMI category (kg/m^2)					
Normal, <25	30	33	36	39	42
Overweight, 25 to <30	40	41	40	40	38
Obese, ≥30	29	26	24	21	20
Alcohol (g/week)	69 ± 132	47 ± 100	37 ± 88	31 ± 68	29 ± 69
Energy intake (kcal/day)	1,753 ± 638	1,574 ± 604	1,555 ± 607	1,581 ± 588	1,709 ± 584
Total fat (% kcal)	36 ± 7	34 ± 6	32 ± 6	32 ± 6	30 ± 6
Saturated fat (% kcal)	14 ± 3	12 ± 3	12 ± 3	11 ± 3	10 ± 3
Monounsaturated fat (% kcal)	14 ± 3	13 ± 3	12 ± 3	12 ± 3	11 ± 3
Polyunsaturated fat (% kcal)	5 ± 1	5 ± 1	5 ± 1	5 ± 1	5 ± 1
Protein (% kcal)	19 ± 4	18 ± 4	18 ± 4	17 ± 4	16 ± 3
Carbohydrate (% kcal)	43 ± 9	47 ± 9	50 ± 8	52 ± 8	55 ± 8
Dietary fiber (g/1,000 kcal)	8 ± 3	10 ± 3	11 ± 4	12 ± 4	14 ± 4
Potassium (mg/1,000 kcal)	1,454 ± 380	1,691 ± 404	1,703 ± 414	1,771 ± 421	1,816 ± 404
Sodium (mg/1,000 kcal)	864 ± 203	889 ± 199	926 ± 207	936 ± 205	956 ± 199
Food group intakes (servings/week)					
Whole grains	4.8 ± 6.4	5.6 ± 6.6	6.9 ± 7.4	7.6 ± 7.0	9.2 ± 7.6
Fruits	7.1 ± 8.1	8.8 ± 8.7	10.0 ± 8.7	11.6 ± 8.9	13.9 ± 9.5
Vegetables	6.6 ± 5.5	7.5 ± 6.0	8.3 ± 6.1	9.0 ± 5.8	11.0 ± 6.6
Nuts	1.7 ± 3.3	2.1 ± 3.4	2.6 ± 3.8	3.0 ± 4.0	4.0 ± 4.5
Legumes	3.1 ± 2.9	3.4 ± 2.8	3.8 ± 3.4	4.0 ± 2.9	5.0 ± 3.5
Coffee and tea	14.2 ± 15.4	15.4 ± 15.8	17.1 ± 15.9	19.1 ± 16.5	20.6 ± 16.8
Fruit juice	2.6 ± 3.7	3.2 ± 3.8	3.8 ± 4.2	4.3 ± 4.7	4.9 ± 4.3
Refined grains	11.8 ± 9.7	11.0 ± 8.6	11.2 ± 9.1	11.5 ± 8.7	13.5 ± 9.1
Potatoes	3.6 ± 3.4	3.6 ± 3.1	3.9 ± 3.3	4.2 ± 3.5	5.0 ± 3.6
Sugar-sweetened beverages	7.2 ± 9.1	6.9 ± 8.1	6.9 ± 7.8	7.5 ± 8.1	8.4 ± 9.0
Sweets and desserts	6.6 ± 7.3	7.2 ± 7.6	7.6 ± 8.0	8.2 ± 8.3	10.1 ± 9.3
Animal fats	3.6 ± 6.1	2.4 ± 5.2	1.7 ± 4.1	1.6 ± 4.2	1.0 ± 3.5
Dairy	13.1 ± 11.1	11.5 ± 9.4	10.9 ± 8.7	10.6 ± 8.4	10.0 ± 7.4
Meat	13.4 ± 6.8	10.4 ± 5.8	9.4 ± 5.4	8.8 ± 5.2	8.3 ± 4.9
Eggs	3.4 ± 3.6	2.2 ± 2.7	1.7 ± 2.3	1.4 ± 1.8	1.1 ± 1.6
Fish and seafood	2.5 ± 2.6	2.2 ± 2.1	2.1 ± 2.0	2.1 ± 2.1	2.1 ± 2.2
Miscellaneous animal-based foods	4.5 ± 4.3	2.9 ± 2.9	2.4 ± 2.8	2.1 ± 2.7	1.7 ± 2.1

Data are means ± SD or percentages unless otherwise indicated.

Table 2—Risk of incident diabetes by quintile and per 10-unit-higher PDI, hPDI, and uPDI scores in the ARIC study

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5	P*	Per 10 units
PDI							
Events	1,114 (20.1)	855 (18.4)	914 (16.3)	632 (15.9)	693 (15.1)		
Model 1	1 (Ref)	0.99 (0.91, 1.09)	0.87 (0.79, 0.95)	0.89 (0.80, 0.98)	0.86 (0.78, 0.95)	0.001	0.92 (0.87, 0.96)
Model 2	1 (Ref)	1.00 (0.91, 1.09)	0.89 (0.81, 0.97)	0.91 (0.83, 1.01)	0.89 (0.80, 0.98)	0.01	0.94 (0.89, 0.99)
Model 3	1 (Ref)	1.02 (0.93, 1.11)	0.92 (0.84, 1.00)	0.97 (0.88, 1.07)	0.93 (0.85, 1.03)	0.23	0.97 (0.92, 1.02)
hPDI							
Events	1,033 (20.3)	957 (18.0)	689 (16.0)	868 (16.5)	661 (15.0)		
Model 1	1 (Ref)	0.92 (0.84, 1.01)	0.83 (0.75, 0.91)	0.84 (0.77, 0.92)	0.79 (0.71, 0.87)	<0.001	0.87 (0.83, 0.91)
Model 2	1 (Ref)	0.94 (0.86, 1.02)	0.86 (0.78, 0.94)	0.88 (0.80, 0.97)	0.85 (0.77, 0.94)	<0.001	0.90 (0.86, 0.95)
Model 3	1 (Ref)	0.96 (0.88, 1.05)	0.89 (0.81, 0.98)	0.94 (0.85, 1.03)	0.92 (0.83, 1.02)	0.04	0.94 (0.90, 0.99)
uPDI							
Events	852 (17.2)	853 (16.0)	890 (16.9)	886 (18.3)	727 (18.2)		
Model 1	1 (Ref)	0.93 (0.84, 1.02)	0.96 (0.88, 1.06)	1.06 (0.97, 1.17)	1.01 (0.92, 1.12)	0.20	1.04 (0.99, 1.09)
Model 2	1 (Ref)	0.91 (0.83, 1.00)	0.94 (0.85, 1.03)	1.01 (0.92, 1.12)	0.95 (0.86, 1.05)	0.97	1.00 (0.96, 1.05)
Model 3	1 (Ref)	0.93 (0.84, 1.02)	0.97 (0.89, 1.07)	1.08 (0.98, 1.19)	1.02 (0.92, 1.13)	0.15	1.04 (1.00, 1.09)

For events, data are incidence rates per 1,000 person-years. Estimates are HR (95% CI) from Cox proportional hazard models. Model 1 covariates include age, sex, race-center, and total energy intake. Model 2 includes model 1 covariates plus education, income, smoking status, physical activity, margarine intake, and alcohol intake. Model 3 includes model 2 covariates and BMI. Ref, reference. *P value for test of trend using median value within each quintile.

age, race, or BMI after accounting for multiple comparisons (all $P_{interaction} > 0.05/12$) (Supplementary Fig. 4).

Sensitivity Analyses

In sensitivity analyses where we redefined plant-based diet scores after leaving one component out at a time, the inverse association between PDI scores and diabetes was no longer significant after exclusion of sweets, meat, eggs, or miscellaneous animal foods (Supplementary Table 3). Removing all animal foods except red meat from PDI scores modestly attenuated inverse associations with diabetes. The inverse associations between hPDI score and incident diabetes risk were robust to exclusion of any single component. However, estimated associations were weaker after removal of meat from scoring and were only marginally attenuated with exclusion of all animal foods except red meat. Removing sugar-sweetened beverages from uPDI scores revealed an inverse association with diabetes risk. Adjustment for time-varying BMI, versus only visit 1 and visit 3 BMI, did not materially alter associations between plant-based diet scores and diabetes risk (Supplementary Table 4). Excluding cases that occurred within the first 5 years of follow-up, higher PDI scores and hPDI scores remained significantly associated with lower risk of diabetes (Supplementary Table 5). Associations were robust to redefinition of incident diabetes based on medication use (Supplementary Table 6).

CONCLUSIONS

Higher adherence to an overall plant-based diet, which includes mostly plant foods and minimizes animal-derived foods, was associated with a lower risk of developing diabetes in this community-based cohort of middle-aged adults. A healthy plant-based diet, which specifically emphasizes fruits, vegetables, legumes, whole grains, nuts, tea, and coffee while minimizing less healthy plant foods (e.g., refined grains, fruit juices) and animal foods, was similarly associated with a lower risk of incident diabetes. However, a plant-based diet incorporating more refined and sweetened plant foods and fewer healthy plant foods was not associated with diabetes risk.

Vegetarian and vegan dietary patterns have previously been associated with lower risk of diabetes in Seventh-day Adventist (3) and Taiwanese Buddhist (4) populations. However, these associations may be confounded by other health behaviors that are common among these populations. Characterization of a plant-based diet with a relative scoring method, with ranking of individuals according to the balance between animal source and plant-based foods consumed, in a general healthy U.S. adult population supports more broadly applicable guidance to consume more plant foods while reducing, without eliminating, animal source foods. Previously, greater adherence to overall and healthy plant-based dietary patterns was associated with lower risk of diabetes in the Nurses' Health Study and Health Professionals Follow-Up Study cohorts, which primarily included educated White adults (7). The findings of our study, conducted in a multisite U.S. cohort of Black and White adults of varying education and income levels, support the generalizability of inverse associations between overall and healthy plant-based dietary patterns with diabetes and are consistent with findings of observational studies in European (16,17) and Asian populations (18,19).

Several pathways may explain why plant-based diets are associated with lower risk of diabetes. First, greater consumption of plant foods, particularly minimally processed forms, increases intake of dietary fibers and bioactive phytochemicals that may inhibit dietary carbohydrate digestion and absorption, promote cellular glucose uptake, alter glucose metabolism (20), and preserve β-cell function and insulin sensitivity by countering oxidative stress and inflammation (20). Dietary fibers and bioactive phytochemicals from plant foods may also alter gut microbial metabolism, thereby reducing intestinal permeability and systemic inflammation, and improving insulin sensitivity (21–23). Although all three plant-based diet indices negatively score consumption of animal-derived foods, only the PDI and hPDI positively score healthy plant food intake. Higher PDI and hPDI scores, but not uPDI scores, were associated with lower diabetes risk. These findings suggest that greater healthy plant food intake may be an important driver of

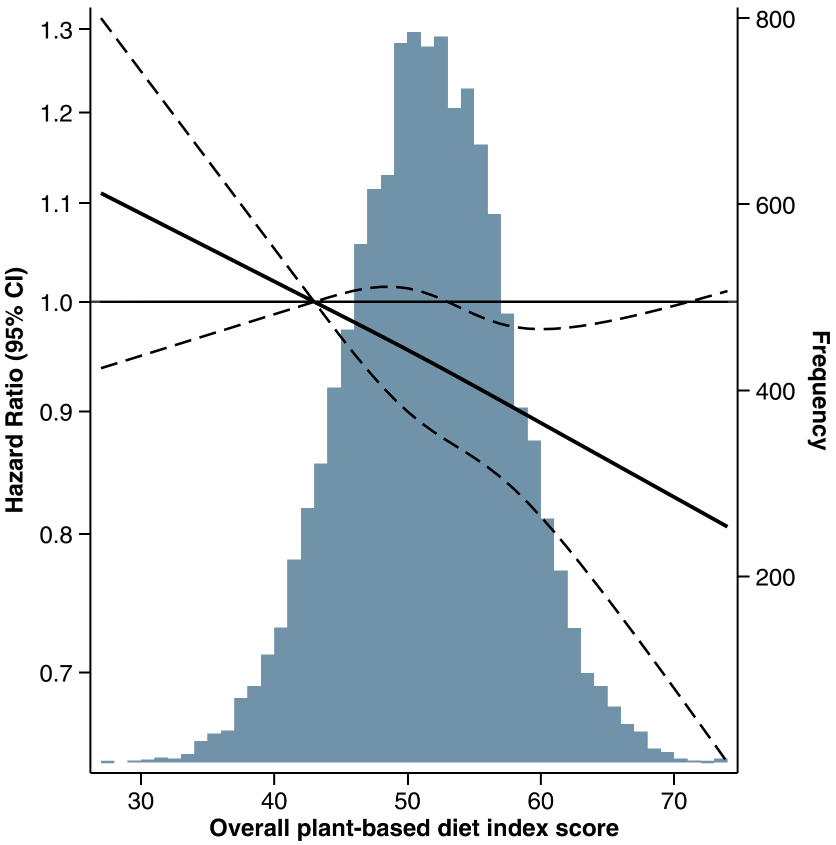

Figure 1—Association between overall PDI score and incident diabetes risk in the ARIC study. Solid line represents the multivariable-adjusted HR for incident diabetes, modeled using restricted cubic spline with three knots at the 10th, 50th, and 90th percentiles of the PDI scores. Dashed lines represent 95% CIs. The reference was set at the 10th percentile of the score. HR adjusted for age, sex, race-center, total energy intake, education, income, smoking status, physical activity, margarine intake, and alcohol intake. The histogram displays the distribution of participants (right *y*-axis) according to baseline PDI scores.

the inverse association between plant-based diets and diabetes risk. Second, minimizing intake of certain animal foods, particularly red and processed meats, and the nutrients (heme iron, saturated fat, sodium) and compounds (curing agents, preservatives, advanced glycated end products) they contain, may help to protect β-cell function and preserve insulin sensitivity (24–26). However, the dietary context in which animal foods are reduced may modify associations with disease, as higher uPDI scores—representing less animal food intake accompanied by greater intakes of unhealthy plant foods—were not associated with diabetes risk. Finally, obesity is a strong risk factor for diabetes (27), and people consuming plant-based diets tend to gain less weight over time (28–30). In our study, adjusting for BMI attenuated associations between overall and healthy plant-based diets and diabetes risk, suggesting that lower adiposity may partly explain the favorable association.

Given that variation in several dietary components is simultaneously modeled by plant-based diet indices, the importance of any individual component in driving the observed associations is not immediately discernible. Therefore, we calculated revised versions of each score to determine whether associations were robust to exclusion of any individual component. Excluding meat from the PDI and hPDI substantially attenuated their inverse associations with diabetes. Excluding all animal components from score calculation except red meat only modestly attenuated estimates for the PDI, while the inverse association between hPDI score and diabetes was essentially unchanged. These analyses suggest that the other (nonred meat) animal foods have little impact on diabetes risk and that the inverse association between plant-based diets and diabetes is primarily explained by greater intakes of plant foods—particularly, healthy plant foods—and not the lower intake of nonred meat animal foods, consistent with the inverse associations observed for Dietary Approaches to Stop Hypertension (DASH) and Mediterranean-style dietary patterns and diabetes risk (31,32). Excluding sugar-sweetened beverages from PDI scores strengthened the inverse associations with diabetes, while a weak inverse association between uPDI scores and diabetes risk emerged after exclusion of sugar-sweetened beverages, suggesting that the risk associated with unhealthy plant foods may mostly be driven by sugar-sweetened beverage consumption.

Strengths of our study include long follow-up in a geographically diverse community-based cohort of Black and White adults in the U.S., which allowed us to explore the generalizability of previously reported inverse associations between plant-based diets and diabetes risk. In addition, use of visit-based laboratory data along with visit- and telephone-based self-report maximized detection of diabetes cases, and associations were confirmed with use of a more specific definition of treated diabetes. We conducted several sensitivity analyses, with careful assessment of the role of individual food components, BMI, and reverse causation in our observed associations. The results of these sensitivity analyses demonstrated the robustness of our findings. Nonetheless, several limitations affect the interpretation of our findings. First, self-reported dietary intake is subject to measurement error (31). We incorporated responses from visit 1 and 3 assessments to improve estimation of usual intake and adjusted for total energy intake to reduce bias (33). Second, diet was assessed several decades ago; the composition of plant-based diets, and their association with diabetes incidence, may differ for modern plant-based diets. Third, categorizing plant foods as healthy versus unhealthy using a food-frequency questionnaire may have resulted in misclassification of some foods that were queried together using a single questionnaire response (34). Fourth, exclusion of participants with missing outcome, exposure, or covariate information may have introduced selection bias. Finally, though we adjusted for measured sociodemographic and lifestyle behaviors that may correlate with self-selected dietary patterns, we cannot exclude the possibility of residual and unmeasured confounding.

In conclusion, greater adherence to a plant-based dietary pattern, particularly one rich in healthy plant foods, was associated with lower risk of diabetes in a cohort of middle-aged U.S. adults. Greater intake of healthy plant foods, and not the lower intake of nonred meat animal foods, was the main component underlying the inverse associations. Emphasizing plant foods may be an effective dietary strategy to delay or prevent the onset of diabetes.

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Author Contributions. V.K.S., H.K., and C.M.R. designed the study. V.K.S. conducted the statistical analysis and wrote the first draft of the manuscript. C.M.R. supervised the study. L.E.C., L.M.S., and E.S. contributed to the interpretation of results. All authors reviewed, edited, and approved the final version of the manuscript. V.K.S. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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