RESEARCH

Association between the atherogenic index of plasma and kidney stones: a nationally representative study

Zhaoxiang Wang[1†], Bing Lu[1†], Li Zhang[1], Fengyan Tang[1], Ying Pan[1] and Shao Zhong[1*]

Abstract

Purpose The atherogenic index of plasma (AIP) is a novel comprehensive lipid index. We aimed to investigate a possible relationship between AIP index and kidney stones in US adults.

Methods This cross-sectional study was conducted among adults with complete AIP index and questionnaire records on kidney stones from the National Health and Nutrition Examination Survey (NHANES) spanning from 2007 to 2018. The AIP index served as the exposure variable, defined as the logarithm of the ratio between triglycerides (TG, mmol/L) and high-density lipoprotein cholesterol (HDL-c, mmol/L). Self-reported history of kidney stones was utilized as the outcome variable. The independent relationship between AIP index and the risk of kidney stones was fully assessed.

Results A total of 14,833 participants were included in this study, with an average AIP index of -0.07 ± 0.01. The proportion of kidney stones progressively increased with higher AIP index tertile intervals (7.33% vs. 9.97% vs. 12.57%, $P < 0.001$). Furthermore, AIP index was found to be independently associated with the risk of kidney stones after adjusting for confounding factors (OR = 1.32, 95% CI 1.08–1.61, $P = 0.006$). Restricted cubic spline (RCS) analysis confirmed the robustness of our results. There was no significant interaction observed based on subgroup analysis stratified by age, gender, race, body mass index (BMI, kg/m^2), smokers, diabetes, hypertension, and cardiovascular disease (P for interaction > 0.05).

Conclusions The AIP index may be a potential epidemiological tool to quantify the role of dyslipidemia in the risk of kidney stones in US adults.

Keywords Atherogenic index of plasma, Dyslipidemia, Kidney stones, NHANES, Population-based study

Introduction

Kidney stones is a prevalent urological disorder formed by the accumulation of inorganic substances (such as crystalline salts) and organic components (such as urinary macromolecules) within the renal parenchyma or pelvicalyceal system [1]. The prevalence and incidence of kidney stones have significantly risen in recent decades, with global estimates ranging from 2 to 20% [2–5]. Common symptoms of kidney stones include lower back pain, hematuria, frequent urination, urgency to urinate, and dysuria. Kidney stones can cause serious complications such as ureteral blockage, urinary tract infections, and ultimately, end-stage renal failure [6]. Surgical intervention is often required for the treatment of kidney stones, imposing significant financial burdens, and escalating public health concerns [1, 7].

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Emerging research suggests that dyslipidemia plays a crucial role in the development of kidney stones, independent of other components of metabolic syndrome such as diabetes and obesity [8–10]. Specific alterations in lipid profiles may serve as potential indicators of unique abnormalities in urine physicochemical properties and the risk of stone formation. The AIP index is a newer and more effective lipid marker, introduced by Dobiásová and Frohlich in 2001 [11]. It is calculated as the logarithmic transformation of TG to HDL-c ratio [11]. Unlike TG or HDL-C levels alone, the AIP index combines both TG and HDL-C levels, providing a comprehensive reflection of the ratio as well as the size of lipoprotein particles, making it a more accurate indicator of dyslipidemia pathogenicity and specificity [12, 13]. Previous studies have demonstrated a strong association between AIP index and various diseases, including cardiovascular diseases, diabetes, metabolic syndrome, and non-alcoholic fatty liver disease [14–17].

However, to our knowledge, there have been no studies exploring the relationship between AIP index and kidney stones. This cross-sectional study utilized data from the NHANES database to investigate the relationship between the AIP index and the risk of kidney stones.

Materials and methods
Data source
This population-based study utilized data from the NHANES, conducted by the National Center for Health Statistics of the Centers for Disease Control and Prevention [18, 19]. NHANES employed a randomized, stratified, multi-stage survey with nationwide representation. Participants underwent physical examinations, health and nutrition questionnaires, and laboratory assessments. The NHANES study protocol was approved by the Ethics Review Board of the National Center for Health Statistics, and detailed design can be accessed at https://www.cdc.gov/nchs/nhanes/. The current study finally consisted of 14,833 eligible participants, obtained by merging data from the NHANES cycles: 2007–2008, 2009–2010, 2011–2012, 2013–2014, 2015–2016, and 2017–2018 (59,842 participants). All participants were aged 20 years or older, not pregnant, had complete data of AIP index, and provided comprehensive questionnaire records on kidney stones.

Exposure and outcome definitions
The AIP index, as an exposure variable, is defined as the logarithm base 10 of the ratio between TG and HDL-c, both measured in mmol/L [20]. The history of kidney stones, which served as the outcome variable, was assessed by posing the question, "Have you or the sample person (SP) ever had a kidney stone?" (ID: KIQ026). Participants who responded "yes" were classified as individuals with kidney stones, whereas those who responded "no" were categorized as individuals without kidney stones. The reliability of self-reported kidney stone history has been established in previous studies [4, 5, 21–24].

Covariate definitions
Demographic data (age, gender, and race) was obtained. It also included various potential covariates such as annual household income, educational level, physical activity, smokers, diabetes, hypertension, cardiovascular disease, BMI, alanine transaminase (ALT, U/L), aspartate transaminase (AST, U/L), gamma-glutamyl transferase (GGT, U/L), glycohemoglobin, fasting plasma glucose (FPG, mmol/L), total cholesterol (TC, mmol/L), low-density lipoprotein cholesterol (LDL-c, mmol/L), serum creatinine (Scr, μmol/L), serum uric acid (SUA, μmol/L), and the estimated glomerular filtration rate (eGFR, ml/min/1.73 m^2). BMI was classified into three categories: < 25, 25–29.9, and ≥ 30 kg/m^2, representing normal weight, overweight, and obesity. The eGFR was calculated using the CKD-EPI creatinine equation, considering factors such as age, gender, race, and Scr [25]. Smokers were identified as current and former smokers. Self-reported diabetes and hypertension were also defined, and the presence of cardiovascular disease was determined based on self-reported history of heart attack, stroke, congestive heart failure, coronary artery disease, or angina. Detailed measurement procedures for all variables in this study were publicly available in the NHANES database.

Statistical analysis
All statistical analyses followed Centers for Disease Control and Prevention guidelines, incorporating a complex multistage cluster survey design, and combining fasting subsample weights from six cycles. Continuous variables were reported as mean with standard error (SE), and categorical variables as percentage. Weighted Student's t-test and chi-squared test were used to compare continuous and categorical variables among multiple groups. Weighted Pearson correlation analysis assessed the association of AIP index with other covariates. Weighted logistic regression models were employed to investigate the associations between TG, HDL-c, TG/HDL, and AIP index and the risk of kidney stones. Three Models were used: Model 1 without covariates adjusted, Model 2 with adjustments for age, gender, and race, and Model 3 with adjustments for multiple covariates including age, gender, race, annual household income, education level, physical activity, smokers, diabetes, hypertension, cardiovascular disease, BMI, ALT, AST, GGT, glycohemoglobin,

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FPG, TC, LDL, Scr, SUA, and eGFR. RCS analysis was used to further elucidate the correlation between AIP index and the risk of kidney stones. Subgroup analyses were performed based on age ($<60/\geq60$ years), gender (female/male), race (white/no white), smokers (ye/no), BMI (normal weight/overweight/obesity), diabetes (yes/no), hypertension (yes/no), and cardiovascular disease (yes/no). The Empower software (http://www.empowerstats.com) and R software (http://www.R-project.org) were used for all statistical analyses. A *P* value < 0.05 was considered statistically significant.

Results

Baseline characteristics of study population

The study finally included 14,833 participants who met the inclusion criteria. Among the entire participant cohort, a total of 1,421 individuals were found to have kidney stones. The average age of the participants was 47.59 ± 0.25 years, and 48.76% of them were male. General characteristics and clinical indicators were compared between the non-kidney stone and kidney stone groups (Table 1). The kidney stone group had higher values in terms of age, male, smokers, diabetes, hypertension, cardiovascular disease, obesity, glycohemoglobin, FPG, TG, Scr, and SUA compared to the non-kidney stone group ($P<0.05$). However, the kidney stone group exhibited significant decreases in moderate physical activity, HDL-c, and eGFR ($P<0.05$). Significant differences in race distribution were also observed between the groups ($P<0.001$). Importantly, the kidney stone group had higher AIP levels than the non-kidney stone group ($P<0.001$).

Clinical features of the participants according to the tertiles of AIP index

Participants were divided into three groups based on their AIP index levels: tertile I, tertile II, and tertile III (Table 2). Compared to the tertile I-AIP group, the tertile II-AIP, and tertile III-AIP groups showed significant increases in age, male, annual household income under $20,000, smokers, prevalence of diabetes, hypertension, cardiovascular disease, obesity, ALT, AST, GGT, glycohemoglobin, FPG, TG, TC, LDL-c, Scr, and SUA ($P<0.001$). Education level above high school and HDL-c exhibited significant decreases ($P<0.001$). Significant differences in race were also observed among the tertile groups ($P<0.001$). No differences in moderate physical activity were observed between groups. Importantly, as AIP levels increased, the prevalence of kidney stones showed a gradual increase (7.33% vs. 9.97% vs. 12.57%, $P<0.001$).

Correlation of AIP index with clinical parameters

Weighted Pearson correlation analysis revealed significant correlations between the AIP index and various variables (Table 3). Specifically, the AIP index was positively correlated with age, male, race, annual household income under $20,000, smokers, prevalence of diabetes, hypertension, cardiovascular disease, BMI, ALT, AST, GGT, glycohemoglobin, FPG, TG, TC, LDL-c, Scr, and SUA, and kidney stones. On the other hand, the AIP index was negatively correlated with education level above high school, HDL-c, and eGFR. After adjusting for age, gender, and race, except for moderate physical activity, AST, and Scr, the AIP index remained significantly correlated with the other variables.

Associations between the AIP and kidney stones

Table 4 presents the association between the AIP index and the risk of kidney stones. The unadjusted models showed that TG, TG/HDL-c, and AIP index were positively associated with an increased risk of kidney stones ($P<0.001$), while HDL-c was negatively associated with the prevalence of kidney stones ($P<0.001$). After adjusting for age, gender, and race, these associations remained statistically significant ($P<0.05$). Further adjustment for multiple covariates revealed that only HDL-c and AIP index were related to the risk of kidney stones. The results indicated a 32% increased risk of kidney stones per unit increase in AIP index (OR = 1.32, 95% CI 1.08–1.61, $P=0.006$). Classification of AIP index into teritles showed that higher AIP teritles levels were associated with a higher prevalence of kidney stones compared to the lowest teritles in the fully adjusted model (*P* for trend < 0.001). Furthermore, the results of RCS analysis also confirmed a positive correlation between AIP index and kidney stones (Fig. 1), with no significant threshold effect observed (*P* for nonlinear > 0.05).

Subgroup analyses

Subgroup analyses were performed to investigate the relationship between AIP index and the risk of kidney stones in various population. Subgroups were stratified by various factors, including age ($<60/\geq60$ years), gender (female/male), race (white/no white), smokers (yes/no), BMI (normal weight/overweight/obesity), diabetes (yes/no), hypertension (yes/no), and cardiovascular disease (yes/no). Figure 2 illustrates the results of these analyses, which revealed no significant interactions among the subgroups (*P* for interaction > 0.05). However, there is a trend towards a stronger association between AIP index and kidney stones in individuals with diabetes.

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Table 1 Baseline characteristics of study population in NHANES from 2007 to 2018, weighted

	Overall (*N* = 14,833)	Non-kidney stones (*N* = 13,412)	Kidney stones (*N* = 1,421)	*P* value
Age (year)	47.59 ± 0.25	46.96 ± 0.26	53.41 ± 0.52	< 0.001
Male gender, % (SE)	48.76 (0.45)	48.20 (0.47)	53.84 (1.67)	0.001
Race, % (SE)				< 0.001
Mexican American	8.64 (0.75)	8.86 (0.76)	6.58 (0.86)	
Non-Hispanic Black	11.20 (0.75)	11.82 (0.79)	5.58 (0.68)	
Non-Hispanic White	66.20 (1.40)	65.20 (1.42)	75.34 (1.82)	
Other Hispanic	5.91 (0.52)	5.96 (0.52)	5.45 (0.81)	
Other Races	8.05 (0.47)	8.16 (0.47)	7.04 (0.86)	
Annual household income (under $20,000), % (SE)	14.18 (0.70)	14.15 (0.70)	14.41 (1.27)	0.814
Education level (above high school), % (SE)	60.77 (1.11)	60.87 (1.11)	59.81 (1.91)	0.528
Moderate physical activity, % (SE)	24.12 (0.57)	24.43 (0.61)	21.29 (1.46)	0.024
Smokers, % (SE)	44.30 (0.78)	43.84 (0.75)	48.57 (2.29)	0.029
Diabetes, % (SE)	9.76 (0.36)	8.83 (0.38)	18.24 (1.26)	< 0.001
Hypertension, % (SE)	33.03 (0.68)	31.47 (0.71)	47.23 (1.85)	< 0.001
Cardiovascular disease, % (SE)	9.12 (0.35)	8.41 (0.37)	15.6 (1.29)	< 0.001
BMI (kg/m^2), % (SE)				< 0.001
Normal weight	29.89 (0.67)	31.07 (0.69)	19.16 (1.32)	
Overweight	32.71 (0.51)	32.82 (0.53)	31.73 (1.77)	
Obesity	37.39 (0.68)	36.11 (0.69)	49.10 (1.84)	
ALT (U/L)	24.98 ± 0.17	24.99 ± 0.19	24.92 ± 0.44	0.874
AST (U/L)	25.09 ± 0.17	25.13 ± 0.18	24.69 ± 0.39	0.315
GGT (U/L)	27.71 ± 0.31	27.59 ± 0.34	28.80 ± 0.89	0.224
Glycohemoglobin (%)	5.64 ± 0.01	5.62 ± 0.01	5.88 ± 0.04	< 0.001
FPG (mmol/L)	5.93 ± 0.02	5.89 ± 0.02	6.31 ± 0.06	< 0.001
TG (mmol/L)	1.38 ± 0.01	1.37 ± 0.02	1.52 ± 0.04	< 0.001
TC (mmol/L)	5.31 ± 0.01	5.31 ± 0.01	5.35 ± 0.04	0.269
HDL-c (mmol/L)	1.40 ± 0.01	1.41 ± 0.01	1.31 ± 0.01	< 0.001
LDL-c (mmol/L)	2.94 ± 0.01	2.94 ± 0.01	2.94 ± 0.03	0.955
Scr (μmol/L)	77.64 ± 0.33	77.19 ± 0.34	81.75 ± 1.50	0.004
SUA (μmol/L)	326.61 ± 1.04	325.46 ± 1.10	337.08 ± 3.12	0.001
eGFR (ml/min/1.73 m^2)	95.47 ± 0.34	96.14 ± 0.36	89.41 ± 0.75	< 0.001
AIP index	-0.07 ± 0.01	-0.08 ± 0.01	0.01 ± 0.01	< 0.001

Values for categorical variables are given as weighted percentage (standard error); for continuous variables, as weighted mean ± standard error. Weighted Student's t-test and chi-squared test were used

Abbreviations: *BMI* body mass index, *ALT* alanine transaminase, *AST* aspartate transaminase, *GGT* gamma-glutamyl transferase, *FPG* fasting plasma glucose, *TG* triglyceride, *TC* total cholesterol, *HDL-c* high-density lipoprotein cholesterol, *LDL-c* low-density lipoprotein cholesterol, *Scr* serum creatinine, *SUA* serum uric acid, *eGFR* estimated glomerular filtration rate, *AIP index* atherogenic index of plasma

Discussion

To our knowledge, this is the first population-based study to explore the relationship between AIP index and the risk of kidney stones. Our research indicated that AIP index is associated with the risk of kidney stones in the US population (OR = 1.32, 95% CI 1.08–1.61, *P* = 0.006). Compared to simple TG, HDL-c, and TG/HDL-c, the AIP index is a promising epidemiological tool that can quantify the role of dyslipidemia in the risk of kidney stones.

Previous studies have shown that serum lipid profiles also affect urinary metabolite profiles and stone composition. Patients with low HDL-c or high TG exhibit significantly increased levels of urinary sodium, oxalate, and uric acid, as well as lower pH values [8, 26]. Additionally, lipid-lowering medications, such as atorvastatin, have been shown to significantly alter urinary citrate, uric acid, and urinary pH levels [27]. Masterson et al. propose that metabolic syndrome may partially explain the impact of dyslipidemia on the formation of kidney

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Table 2 Baseline characteristics of study population according to the tertiles of AIP index, weighted

	Tertile 1	Tertile 2	Tertile 3	*P* value
Age (year)	45.83 ± 0.41	47.96 ± 0.37	49.09 ± 0.30	< 0.001
Male gender, % (SE)	36.51 (0.90)	49.09 (0.91)	61.43 (0.91)	< 0.001
Race, % (SE)				< 0.001
Mexican American	6.27 (0.65)	9.06 (0.88)	10.71 (0.95)	
Non-Hispanic Black	16.55 (1.16)	10.85 (0.74)	5.87 (0.50)	
Non-Hispanic White	64.07 (1.56)	66.18 (1.55)	68.49 (1.49)	
Other Hispanic	5.15 (0.58)	6.13 (0.55)	6.50 (0.65)	
Other Races	7.96 (0.62)	7.77 (0.54)	8.43 (0.61)	
Annual household income (under $20,000), % (SE)	12.42 (0.78)	14.63 (0.86)	15.59 (0.95)	0.001
Education level (above high school), % (SE)	67.18 (1.36)	59.81 (1.21)	54.92 (1.39)	< 0.001
Moderate physical activity, % (SE)	24.60 (0.84)	23.13 (0.88)	24.63 (1.01)	0.114
Smokers, % (SE)	37.79 (1.11)	43.40 (1.06)	52.15 (1.01)	< 0.001
Diabetes, % (SE)	4.72 (0.37)	8.75 (0.46)	16.16 (0.72)	< 0.001
Hypertension, % (SE)	24.38 (0.96)	33.33 (1.11)	41.94 (1.03)	< 0.001
Cardiovascular disease, % (SE)	6.54 (0.49)	8.40 (0.48)	12.61 (0.63)	< 0.001
BMI (kg/m^2), % (SE)				< 0.001
Normal weight	48.70 (1.07)	26.86 (1.01)	12.95 (0.65)	
Overweight	29.65 (0.76)	34.68 (0.97)	33.96 (0.92)	
Obesity	21.65 (0.87)	38.46 (0.92)	53.09 (1.07)	
ALT (U/L)	21.39 ± 0.31	24.25 ± 0.28	29.57 ± 0.35	< 0.001
AST (U/L)	24.39 ± 0.29	24.51 ± 0.26	26.42 ± 0.32	< 0.001
GGT (U/L)	22.26 ± 0.50	26.56 ± 0.52	34.69 ± 0.65	< 0.001
Glycohemoglobin (%)	5.44 ± 0.01	5.60 ± 0.01	5.90 ± 0.02	< 0.001
FPG (mmol/L)	5.53 ± 0.02	5.83 ± 0.02	6.47 ± 0.05	< 0.001
TG (mmol/L)	0.69 ± 0.00	1.16 ± 0.01	2.35 ± 0.03	< 0.001
TC (mmol/L)	5.13 ± 0.02	5.30 ± 0.02	5.51 ± 0.02	< 0.001
HDL-c (mmol/L)	1.75 ± 0.01	1.36 ± 0.01	1.07 ± 0.00	< 0.001
LDL-c (mmol/L)	2.70 ± 0.02	3.02 ± 0.02	3.12 ± 0.02	< 0.001
Scr (µmol/l)	74.63 ± 0.54	77.69 ± 0.44	80.79 ± 0.58	< 0.001
SUA (µmol/L)	294.93 ± 1.47	326.88 ± 1.57	360.02 ± 1.84	< 0.001
eGFR (ml/min/1.73 m2)	98.22 ± 0.52	94.70 ± 0.46	93.33 ± 0.44	< 0.001
Kidney stones, % (SE)	7.33 (0.55)	9.97 (0.51)	12.57 (0.61)	< 0.001

Values for categorical variables are given as weighted percentage (standard error); for continuous variables, as weighted mean ± standard error. Weighted Student's t-test and chi-squared test were used

stones, as dyslipidemia is one of the diagnostic criteria for metabolic syndrome [28, 29]. Dyslipidemia is also closely associated with insulin resistance. Additionally, elevated levels of AIP index have been suggested as indicative of insulin resistance [30]. Insulin resistance can impair ammonia excretion and increase renal tubular uptake of citrate, contributing to high urinary acidity and reduced citrate levels, respectively, which are major risk factors for uric acid and calcium stone formation [31]. Moreover, evidence suggests that dyslipidemia, which mediates inflammation, is an independent risk factor for increased stone formation [21, 32, 33]. Some scholars also suggest that the accumulation of atherosclerotic plaques may lead to calcification, subsequently eroding into the

Bellini collecting ducts, further increasing the likelihood of stone growth [34]. It is evident that dyslipidemia can have a multifactorial impact on the formation of kidney stones.

In this study, we observed a correlation between high TG levels, low HDL-c levels, TG/HDL-c, and AIP index with the formation of kidney stones. However, it is worth noting that, after adjusting for various confounding factors, only HDL-c and AIP index maintained this correlation. Previous studies have shown that AIP index, the logarithmic ratio of TG to HDL-C, not only quantifies lipid metabolism, but also shows significant associations with small dense low-density lipoprotein-cholesterol (sdLDL-C) and glucose metabolism [35, 36].

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Table 3 Pearson correlation analysis results of AIP index with other parameters in the whole study population, weighted

	Non-adjusted	Adjusted for age, gender, and race
Age (year)	0.064**	-
Gender (male)	0.207**	-
Race	0.062**	-
Annual household income (under $20,000)	0.052**	0.058**
Education level (above high school)	-0.111**	-0.102**
Moderate physical activity	0.014	-0.009
Smokers	0.123**	0.078**
Diabetes	0.148**	0.122**
Hypertension	0.124**	0.103**
Cardiovascular disease	0.078**	0.046**
BMI (kg/m^2)	0.300**	0.319**
ALT (U/L)	0.191**	0.141**
AST (U/L)	0.056**	0.017
GGT (U/L)	0.157**	0.103**
Glycohemoglobin (%)	0.218**	0.179**
FPG (mmol/L)	0.254**	0.201**
TG (mmol/L)	0.758**	0.893**
TC (mmol/L)	0.209**	0.177**
HDL-c (mmol/L)	-0.725**	-0.724**
LDL-c (mmol/L)	0.180**	0.184**
Scr (umol/l)	0.060**	0.003
SUA (umol/L)	0.298**	0.241**
eGFR (ml/min/1.73 m^2)	-0.095**	-0.065**
Kidney stones	0.066**	0.056**

** $P < 0.01$

Table 4 Logistic regression analysis results of AIP index and kidney stones, weighted

Kidney stones	OR (95%CI), *P* value		
	Non-adjusted model 1	Adjusted model 2	Adjusted model 3
Continuous			
TG	1.07 (1.03, 1.11), < 0.001	1.04 (1.00, 1.08), 0.031	1.03 (0.98, 1.07), 0.252
HDL-c	0.58 (0.50, 0.67), < 0.001	0.59 (0.50, 0.68), < 0.001	0.73 (0.62, 0.87), < 0.001
TG/HDL-c	1.04 (1.02, 1.07), < 0.001	1.03 (1.01, 1.06), 0.013	1.03 (0.99, 1.06), 0.103
AIP index	1.92 (1.64, 2.25), < 0.001	1.58 (1.34, 1.88), < 0.001	1.32 (1.08, 1.61), 0.006
Categories			
Tertile 1	1.00	1.00	1.00
Tertile 2	1.41 (1.23, 1.63), < 0.001	1.25 (1.08, 1.45), 0.003	1.12 (0.95, 1.30), 0.169
Tertile 3	1.76 (1.54, 2.03), < 0.001	1.46 (1.27, 1.69), < 0.001	1.23 (1.04, 1.44), 0.014
P for trend	< 0.001	< 0.001	< 0.001

Adjusted model 2: age, gender, and race were adjusted

Adjusted model 3: additionally adjusted for annual household income, education level, physical activity, smokers, diabetes, hypertension, cardiovascular disease, BMI, ALT, AST, GGT, glycohemoglobin, FPG, TC, LDL, Scr, SUA, and eGFR

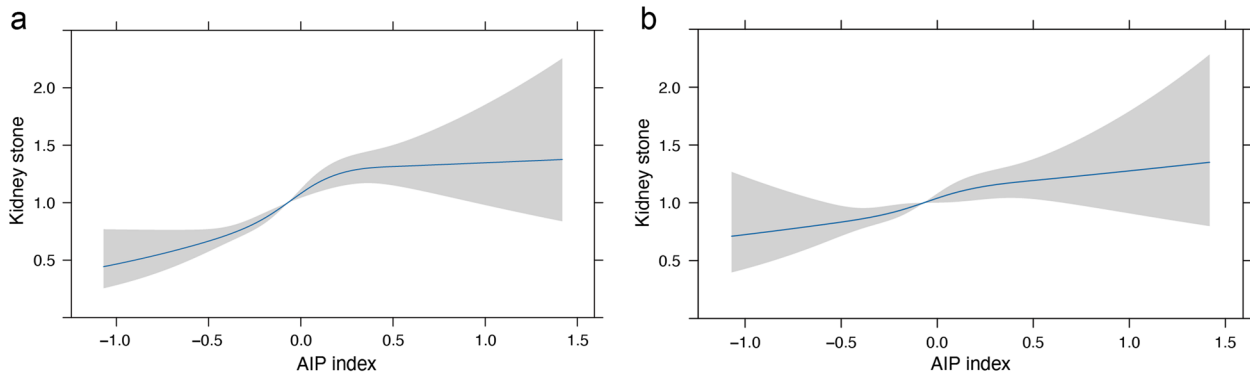*OR* odds ratio, *95% CI* 95% confidence interval

Fig. 1 RCS results of AIP index and the risk of kidney stones (**a** no covariates adjusted; **b** adjusted for age, gender, race, annual household income, education level, physical activity, smokers, diabetes, hypertension, cardiovascular disease, BMI, ALT, AST, GGT, glycohemoglobin, FPG, TC, LDL, Scr, SUA, and eGFR)

Kidney stones	Sample		OR(95%CI), P value	P for interaction
Age				
<60	750/9692		1.34 (1.05, 1.70), 0.018	0.498
≥60	671/5141		1.51 (1.13, 2.03), 0.006	
Gender				
Female	636/7600		1.46 (1.10, 1.95), 0.010	0.694
Male	785/7232		1.36 (1.06, 1.74), 0.014	
Race				
White	657/6156		1.31 (1.00, 1.72), 0.050	0.477
Non-white	764/8677		1.49 (1.15, 1.92), 0.002	
Smoker				
No	724/8211		1.52 (1.17, 1.98), 0.002	0.347
Yes	696/6600		1.29 (0.99, 1.67), 0.055	
BMI				
Normal weight	271/4266		1.24 (0.80, 1.92), 0.335	0.667
Overweight	468/4833		1.55 (1.14, 2.10), 0.005	
Obese	664/5552		1.35 (1.02, 1.79), 0.033	
Diabetes				
No	1088/12804		1.28 (1.03, 1.59), 0.023	0.067
Yes	332/2021		1.92 (1.31, 2.82), <0.001	
Hypertension				
No	703/9266		1.54 (1.19, 2.00), 0.001	0.276
Yes	717/5547		1.27 (0.97, 1.65), 0.080	
Cardiovascular disease				
No	1146/13127		1.33 (1.07, 1.64), 0.009	0.181
Yes	275/1706		1.82 (1.18, 2.79), 0.006	

Fig. 2 Subgroup analysis results based on age, gender, race, smokers, BMI, diabetes, hypertension, and cardiovascular disease

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Other studies have also demonstrated that AIP index is a simple and useful tool for identifying insulin-resistant patients at higher cardiovascular risk, proving more effective than the conventional visceral adiposity index [36, 37]. Therefore, consistent with previous research findings, we also believe that the AIP index, as a novel comprehensive lipid indicator, may have clinical significance that surpasses the impact of individual TG and HDL-c levels and the simple ratio of the two on kidney stone formation [38, 39]. The AIP index is anticipated to serve as a quantifiable marker that connects metabolic syndrome and obesity to the risk of kidney stones. Moreover, the comparative efficacy of the AIP index versus other metabolic indicators, such as the triglyceride-glucose index (TyG), requires further investigation.

This study used a nationally representative sample that adequately represented the various ethnic groups in US adults [24]. However, it is important to recognize the limitations of our study. Firstly, the cross-sectional design used does not allow us to establish a cause-and-effect relationship between the AIP index and the risk of kidney stones. Prospective cohort studies and intervention trials are needed to determine if such a relationship exists. Secondly, although adjustments were made for some common confounding factors in this study, it did not consider the history of diseases like metabolic syndrome and non-alcoholic fatty liver disease, the use of medications such as lipid-lowering drugs that affect lipid levels, or dietary habits including water and meat consumption, which could lead to biased findings. Thirdly, given that our research is an exploratory preliminary analysis of existing data, we were unable to gather detailed information on kidney stones, such as their quantity and composition, which limited further analysis. Lastly, our study was conducted using a sample from the US population, so further research is needed to confirm the generalizability of our findings.

Conclusion
In a nationally representative study of an adult population in the United States, we uncovered a compelling correlation between the AIP index and a heightened susceptibility to kidney stones.

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